NASA/CR—1999–209256

A Survey of Radiation Measurements Made Aboard Russian Spacecraft in Low-Earth Orbit

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Prepared for Marshall Space Flight Center
under Contract NAS8–40294
and sponsored by
the Space Environments and Effects Program
managed at the Marshall Space Flight Center

National Aeronautics and
Space Administration

Marshall Space Flight Center • MSFC, Alabama 35812

March 1999

Available from:

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TABLE OF CONTENTS

Introduction

The accurate prediction of ionizing radiation exposure in low Earth orbit is necessary in order to minimize risks to astronauts, spacecraft and instrumentation. To this end, models of the radiation environment, the AP-8 trapped proton model and the AE-8 trapped electron model, have been developed for use by spacecraft designers and mission planners. It has been widely acknowledged for some time now by the space radiation community that these models possess some major shortcomings. Both models cover only a limited trapped particle energy region and predictions at low altitudes are extrapolated from higher altitude data. With the imminent launch of the first components of the International Space Station and with numerous constellations of low-Earth orbit communications satellites now being planned and deployed, the inadequacies of these trapped particle models need to be addressed. Efforts are now underway both in the U. S. and in Europe to refine the AP-8 and AE-8 trapped particle models. Most notably, the NASA Space Environment and Effects office at the Marshall Space Flight Center is sponsoring several studies of the trapped radiation environment in an effort to improve the predictive capability of the models in low Earth orbit and to evaluate model uncertainties for spacecraft design.

A part of any effort to model real world phenomena is to validate the model based on actual measurements. In the case of the trapped radiation environment in low Earth orbit, a wealth of such measurements have been made aboard Russian satellites and spacecraft. Some of this data is quite old, but has only recently been made available. Other sets of measurement are the results of recent cooperation between different institutions in a number of different countries with the Russian Space Agency. This report is an attempt to collect a significant fraction of this data in one place for use in validation of trapped radiation models at low altitudes. This work was performed under subcontract from Science Applications International Corporation as part of a study entitled "Trapped Radiation Model Uncertainties for Spacecraft Design" conducted for the NASA Space Radiation Environments and Effects Office, NASA Marshall Space Flight Center, Huntsville, Alabama.

Chapter 1 focuses on absorbed dose measured as a function of shielding depth on the exterior surface of Russian satellites. This data hopefully presents a minimum of difficulty in modeling since the shielding surrounding the detectors is relatively simple. The remaining chapters of this report are devoted to measurements made aboard the Russian Mir Space Station. This data is especially timely since the International Space Station will occupy a similar orbit to that of the Mir. Chapter 2 is a survey of measurements made with active detectors aboard Mir. Chapter 3 contains measurements of LET spectra carried out using plastic nuclear track detectors and the JSC Tissue Equivalent Proportional Counter. Finally in Chapter 4, absorbed dose measurements made inside the main Core module of the Mir Space Station by a large number of different institutions are intercompared. Since most of these measurements were made for dosimetric purposes, dose is given as dose in tissue unless otherwise noted. If dose in Si is desired, tissue dose must be multiplied by a suitable conversion factor.

Chapter 1 – Dose Measurements on the Exterior of Russian Spacecraft

Experiments to measure dose under thin shielding (<1 g/cm^2) have been carried out on at least ten Soviet/Russian satellite missions over the last twenty years by a number of different research laboratories. Most of these missions were part of the Soviet/Russian Biocosmos (now Bion) program of recoverable satellites. Measurements of dose using a variety of Thermoluminescent Detector (TLD) materials were carried out both inside and on the outer surface of these spacecraft. In general the dose measurements made inside the spacecraft have been of limited use for purposes of trapped particle environment and transport model validation since the shielding within the spacecraft at the location where the measurements were made was not known. Measurements of dose as a function of shielding depth made under thin shielding (<1 g/cm^2) on the outer surface of these spacecraft provide a much simpler situation to model and can be used in assessing predictions made by the AP8 and AE8 trapped proton and electron models, respectively. Three other experiments to measure dose under thin shielding using TLDs have been carried out, one on the STS-46 Space Shuttle mission and two on the Russian Mir Space Station. This includes a recent measurement of dose as a function of shielding depth carried out in 1997 during the NASA/Mir Science Program. Table 1-1 lists the missions, exposure dates and duration, and orbital parameters on which dose rate was measured as a function of shielding depth on the spacecraft exterior.

Table 1-1. Flight Parameters of Space Missions on which Dose Rate was measured as a function of shielding on the spacecraft exterior.

Mission	Dates	Exposure (days)	Orbital Parameters apogee (km)	perigee (km)	inclination
Cosmos 936	8/3/77-8/22/77	18.5	419	224	62.8°
Cosmos 1129	9/25/79-1-/14/79	18.56	394	226	62.8°
Cosmos 1514	12/14/83-12/19/83	5*	260	215	82°
Cosmos 1571	6/11/84-6/26/84	14.5	398	218	70°
Cosmos 1760	6/19/86-7/2/86	14.0	398	208	70°
Cosmos 1781	9/17/86-10/1/86	14.0	383	297	70.4°
Cosmos 1887	9/29/87-10/12/87	13.0	406	224	62.8°
Cosmos 2044	9/15/89-9/29/89	14.0	294	216	82.3°
Mir-91	6/24/91-7/28/91	34**	~400	~400	51.65°
EIOM3 (STS-46)	7/31/92-8/7/91	7.97	420	520	28.5°
Photon 8	10/8/92-10/23/92	15.6	359	220	62.8°
Mir-23/Mir-24	4/28/97-9/5/97	130†	~400	~400	51.65°

*Alternate source states mission duration was actually six days.

**Dates and duration reflect period that detectors were exposed on the outer surface of Mir. The detectors were delivered to Mir on 6/6/91 and returned to Earth on 8/10/91. They were stored in a high shielding area inside Mir before and after external exposure.

†Dates and duration reflect period that detectors were exposed on the outer surface of Mir. The detectors were delivered to Mir on 1/12/97 and returned to Earth on 10/5/97. They were stored in a high shielding area inside Mir before and after external exposure.

1.1 EXPERIMENTAL METHODOLOGY

On a typical Biocosmos mission, a variety of biological subjects including Rhesus monkeys, rats, and plant seeds were flown usually for a period of approximately two weeks in low Earth orbit. The Biocosmos satellite, pictured in Figure 1-1, is essentially a modified Vostok spacecraft and is launched atop a Vostok booster. Nearly all the launches in the Biocosmos program took place at the Plesetsk Cosmodrome in central Russia. Since the collapse of the Soviet Union, the Biocosmos program has continued under the name Bion. Participants from a number of different countries including Russia, USA, Hungary, Czechoslovakia and Germany have carried out experiments on Biocosmos satellites.

Measurements of dose using TLDs on the exterior surface of the Biocosmos satellites were carried out utilizing a device that looks somewhat like an old-fashioned waffle iron and functions like a clam shell. Figure 1-2 shows one of the 'waffle iron' containers in the open "exposed" configuration. The circular components in the center of the container are the aluminum holders that house the stacks of thin TLDs used to measure dose. A number of these 'waffle irons' are positioned around the outer circumference of the retrievable portion of the spacecraft and contain a variety of experiments requiring direct exposure to the space environment. The spacecraft is launched with the containers in the open position, protected by the nose faring of the booster. Once the faring is jettisoned on-orbit, the interior of the containers are exposed to the external space environment. The containers then automatically close prior to deorbit to protect the experiments from the heat of reentry.

Each 'waffle iron' container can hold a number of TLD stacks. TLD stacks are housed in holders, usually made of aluminum, but some have also contained brass or acrylic components. A diagram of a thin TLD stack and holder of the type utilized by US investigators is pictured in Figure 1-3. TLDs are stacked on top of each other to a thickness of approximately 1 cm inside the acrylic holder. The entire stack consists of approximately 32 TLDs. The upper twenty TLDs are ~91.6 μm thick while the lower twelve TLDs are ~889 μm thick. The loaded acrylic holder is then capped by two layers of aluminized Kapton foil measuring 15 μm or 2.16×10^{-3} g/cm^2 in thickness. This thickness represents the minimum shielding through which the top-most TLD is exposed. Differences in stack construction and foil cover thickness are noted for each specific experiment.

Following exposure during the mission and successful recovery, the TLDs are returned to the laboratory and read out using a standard, commercial TLD reader. Dose is determined as a function of the position of each TLD within the stack. This position information is then converted to shielding depth in units of g/cm^2. Dose rate is determined by dividing dose by the duration of the mission. While, strictly speaking, the period of low shielding exposure is somewhat shorter than the total mission duration, being only that time when the 'waffle iron' containers were in the open position, no information on this length of time is available for any of the Biocosmos missions.

Measurements of dose as a function of shielding depth for thin shielding geometries have been carried out by a number of different research groups on Biocosmos satellites. These groups include the Department of Spacecraft Radiation Safety at the Institute for Biomedical Problems (IBMP) in Moscow, Russia, the Physics Research

Laboratory of the University of San Francisco (USF) in California, the Central Research Institute for Physics in Budapest, Hungary, the Institute of Radiation Dosimetry in Prague, Czechoslovakia (now the Czech Republic), the Technische Universitat Dresden, Dresden, German Democratic Republic (now part of the Federal Republic of Germany), and the DLR Institute of Aerospace Medicine, Koln, Federal Republic of Germany. Each group carried out dose measurements using nearly the same technique with some important exceptions that are noted below. Similar measurements have also been made aboard the Russian Mir Orbital Station by the IBMP and USF groups in 1991 and aboard the U.S. Space Shuttle mission STS-46 (EIOM3 experiment) by the USF group in 1992. The most recent results from this type of dose/depth measurement comes from the USF experiment carried out on the Mir Station in 1997 as part of the NASA/Mir Science Program.

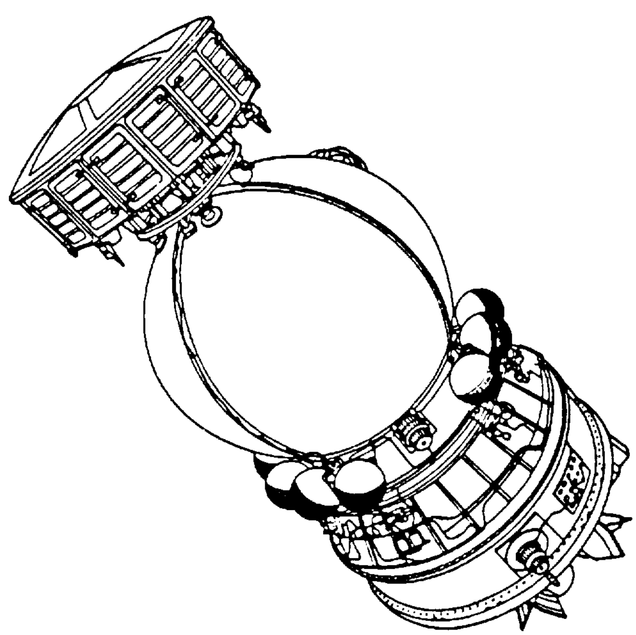


Figure 1-1. Biocosmos recoverable satellite.

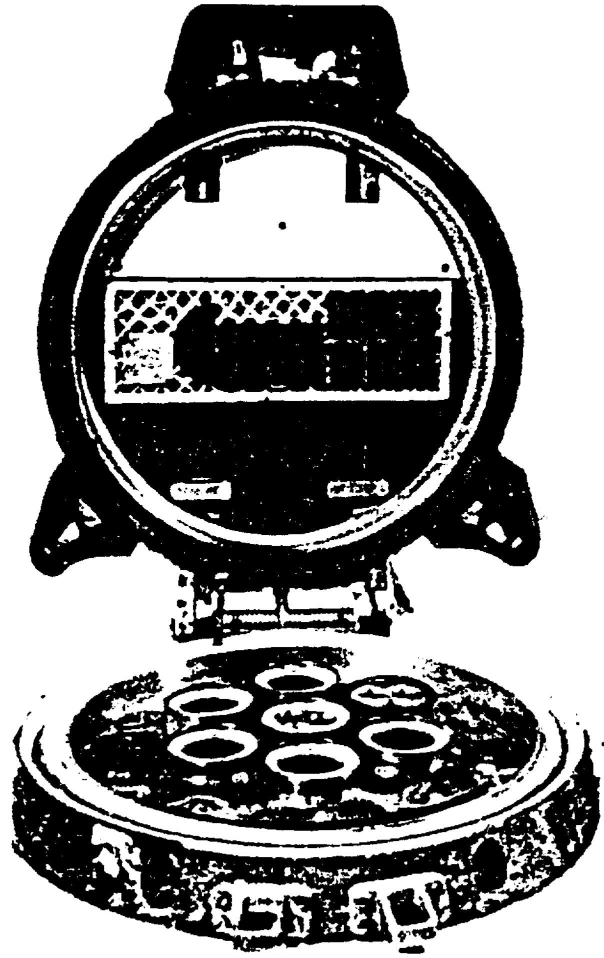


Figure 1-2. 'Waffle Iron' container for experiments requiring exposure to the external space environment. Experiments are placed both in the base and on the inner lid.

Duration and orbital parameters of each mission are listed in Table 1-1. The Cosmos missions were all of high inclination, ranging from 62.8° to 82.3°. The high inclination orbits exposed the spacecraft to the low energy electron component found near the poles. In addition the Cosmos missions tended to elliptical. The only low inclination orbit is that of STS-46 at 28.5°. The low inclination of this orbit translates into relatively lengthy passage through the South Atlantic Anomaly (SAA) and correspondingly greater exposure to trapped protons. The measurements aboard the Mir Orbital Station are for a 400 km, 51.65° orbit, the same orbit that will be occupied by the ISS.

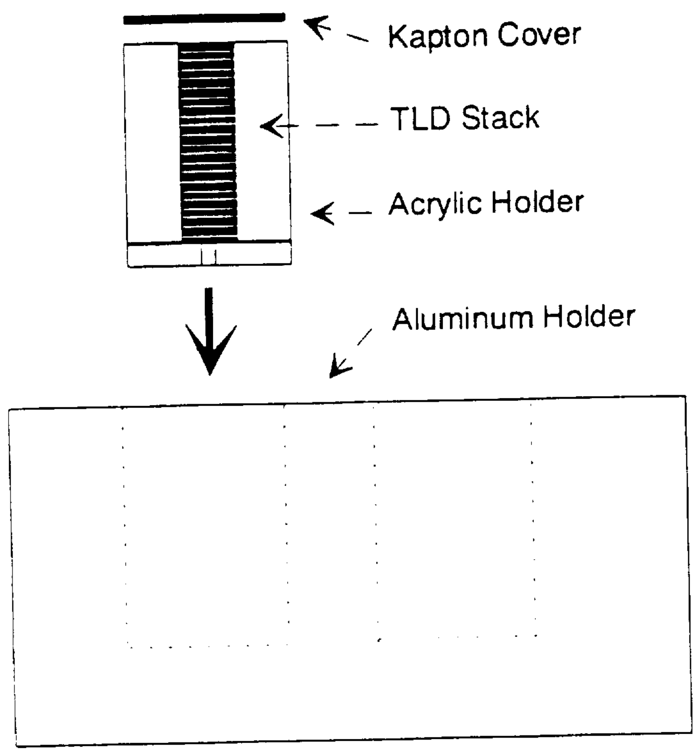


Figure 1-3. Diagram of the USF designed thin TLD stack used to measure dose as a function of shielding depth on the spacecraft exterior.

1.2 EXPERIMENTAL RESULTS

1.2.1 Cosmos 936 and Cosmos 1129

The first measurements of dose made under low shielding on the exterior of a Cosmos type satellite were made aboard Cosmos missions 936 and 1129 in August 1977 and September-October 1979, respectively by the USF group. Figure 1-4 show dose rate as a function of shielding measured for the two missions[1]. Both orbits were at an inclination of 62.8° and had similar altitudes. The apogee of Cosmos 936 was 419 km and for Cosmos 1129 was 394 km. The perigees of Cosmos 936 and 1129 were 224 and 226 km respectively. The duration of each mission was ~18.5 days. Thick TLDs of ~0.23 g/cm^2 shielding were used on both experiments so the measured dose represents the accumulated dose at that shielding depth. For this reason it may be difficult to accurately model the exposure from these first two missions.

1.2.2 Cosmos 1514

Measurements of dose as a function of depth under low shielding on Cosmos 1514 were made by the Hungarian group of Szabo et al.[2] at the Central Research Institute for Physics, Budapest, Hungary. This experiment differed considerably from the other dose measurements made on Cosmos missions in that instead of standard TLD chips being stacked in a holder, the thermoluminescent (TL) material was combined with Teflon to form solid rods. Specifically, $CaSO_4$:Dy TLD in powder form was combined with powdered Teflon in a mass ratio of 1:3, cold-pressed and annealed into rods measuring 5.8 mm in diameter and ranging in length from 6 to 15 mm. The rods were then inserted into cylindrical brass collimators, 2 mm in thickness, and then placed in Al holders and capped with a 1.5 mg/cm^2 Aluminum foil cover[3]. Following the mission, the TL/Teflon rods were sliced into disks ranging in thickness from 25 to 100 μm using a microtome. The mass of each disk was measured and the disk was readout using a custom-built Hungarian TLD reader. In this way it was possible to measure dose for extremely small increments of shielding. Control TL/Teflon rods were exposed to a standard ^{60}Co source for purposes of calibration.

The paper by Szabo et al.[2] which presents this data, incorrectly cites the mission number as being Cosmos 1451, not Cosmos 1514. In addition this paper reports that the length of this mission was six days. Other sources have stated that the mission duration for Cosmos 1514 was five days and this value was used in converting dose to dose rate. Cosmos 1514 flew in an elliptical 82° inclination orbit with an apogee of 260 km and a perigee of 218 km. Figure 1-5 shows the two TLD depth/dose rate profiles measured by Szabo et al. As with all the other data presented in this report, the depth plotted along the x-axis is measured from the top of the stack (the 1.5 mg/cm^2 aluminum cover) down through the center of the rod (stacks in all other cases).

1.2.3 IMBP Measurements on Cosmos Missions

The Institute of Biomedical Problems in Moscow, Russia measured depth/dose profiles on a number of Cosmos satellite missions in the 1980s, including on Cosmos 1571, Cosmos 1760, Cosmos 1781 and Cosmos 1887[4]. These measurements were carried out using Czechoslovak and Russian alumophosphate glass TLDs of 0.1, 0.3, 0.4, 0.5, and 1 mm thickness. Total thickness of the TLD stacks varied from 5 to 20 mm. Each detector stack had a diameter of 8 mm. Aluminum foil or aluminized polyester film ranging in thickness from 4.5 to 10 μm was used to cover the TLD stacks in their Al holders.

Only one set of measurements is available for the Cosmos 1571 mission and the dose rate as a function of shielding depth is plotted in Figure 1-6. Cosmos 1571 was a 70° inclination mission with an apogee and perigee of 398 and 218 km, respectively. The duration of the mission was reported as being 14.5 days. The thickness of the protective cover was 2.3×10^{-3} g/cm^2.

Dose rate as a function of shielding depth was measured in four separate stacks on Cosmos 1760. These measurements are presented in Figure 1-7. Cosmos 1760 was a 14.0 day, 70° inclination mission with an apogee and perigee of 398 and 208 km, respectively. The thickness of the protective cover was 1.25×10^{-3} g/cm^2.

Four separate measurements of dose rate as a function of shielding depth are presented in Figure 1-8 for the Cosmos 1781 mission. Cosmos 1781 was also a 14.0 day mission. Its orbit was of 70.4° inclination, 383 km apogee, and 297 km perigee. The thickness of the protective cover was 1.25×10^{-3} g/cm^2. Akatov et al.[4] reports that the average dose rate in the first 100 μm of the TLD stacks was 9.36 Gy/day.

1.2.4 Cosmos 1887

Dose as a function of shielding depth was measured by a number of different research groups on Cosmos 1887. While all the groups employed TLDs, the type of TL material varied from experiment to experiment. All the measurements were carried out using stacks of thin TLDs placed in brass or aluminum collimators. Dose was determined as a function of TLD position in the stack which was then converted to shielding depth. The TLD stacks were covered with different thicknesses of foil to protect them from direct sunlight and placed inside one of the several 'waffle iron' containers used on the mission. Cosmos 1887 was a 62.8° inclination mission with an apogee of 406 km and a perigee of 224 km. The mission duration was 13.0 days.

Four sets of depth/dose measurements were carried out by Charvat et al. of the Institute of Radiation Dosimetry, Prague, Czechoslovakia[5]. Set 1, flown in container B8-2, contained several TLDs of $CaSO_4$:Dy in Teflon manufactured by Teledyne Isotopes. Each TLD had a thickness of ~0.4 mm and the stack was covered by a 35 μm thick gold foil. Set 1 also contain two stacks of alumophosphate (Al-P) glass TLDs. The upper four Al-P detectors were 0.5 mm in thickness while the remaining two or three Al-P detectors were 1 mm thick. The Al-P stacks were covered by a layer of 30 μm thick gold foil. Set 2 was flown in the B8-1 container and consisted of one stack of 10 $CaSO_4$:Dy/teflon detectors and two stacks of Al-P detectors like those described in Set 1. Each stack was protected by a layer of 35 μm thick gold foil. Set 3, flown in container B8-3, consisted of one stack of 10 $CaSO_4$:Dy/teflon detectors, one stack of 13 Al-P 0.4 mm thick Al-P detectors, and one stack of five 1 mm thick Al-P detectors. Set 4, flown in container B8-4, contained one stack of 10 $CaSO_4$:Dy/teflon detectors and two stacks of 1 mm thick Al-P detectors. Figures 1-9, 1-10, and 1-11 show dose rate as a function of shielding depth for the four sets of Czech detectors flown on Cosmos 1887. The results are presented in terms of ^{60}Co radiation in small tissue volume. Thus they under register the dose from protons and higher Z particles which are less than 100% efficient in producing signal in TLDs.

Similar measurements of dose behind thin shielding were carried out on Cosmos 1887 by the Schmidt et al. group of the Technishe Universitat Dresden, Dresden, Germany[6]. The Schmidt group utilized a TLD material and fabrication technique similar to that developed by Szabo et al. for Cosmos 1514. Luminophosphor CaF_2:Mn Tl material (30% by mass) was embedded in polytetraflourethane (PTFE). The CaF_2:Mn/PTFE material was sliced into thin layers ranging from 50 to 100 μm (12.5 to 25.0 mg/cm^2) in thickness. The TL shavings were then annealed between glass plates and stacked inside brass collimators. The collimators were capped with a layer of foil consisting of 3 μm thickness of polyester and a 0.3 μm thickness of aluminum. Following recovery of the experiment the thin TL material was read out. Figures 1-12, 1-13 and 1-14 show the results in units of ^{60}Co γ-ray dose rate. Schmidt et al.[6] report that the response of CaF_2:Mn/teflon to 1 MeV protons is a factor of ~5 below that for ^{60}Co γ-rays.

Measurements of dose were made at known shielding depths in the external 'waffle iron' containers of Cosmos 1887 by Reitz et al.[7] of DLR, Koln, Germany. These measurements differ from the other experiments to measure depth/dose profiles in that individual TLDs were placed at varying shielding depths throughout the containers, but not stacked one atop another in a collimator. Three types of LiF TLDs were used: TLD-100, TLD-600 and TLD-700, all produced by Harshaw Chemical. Table 1-2 summarizes the results of the DLR dose measured on Cosmos 1887. TLD-600 is ^{6}LiF while TLD-700 is ^{7}LiF. Due to the larger neutron absorption cross section of ^{6}Li, thermal and epithermal neutrons register in TLD-600 but not in TLD-700. The difference in measured dose between the two TLD materials gives an indication of the thermal and epithermal neutron contribution to total dose. Figure 1-15 shows dose rate as a function of shielding depth measured in TLD-700 in the exterior containers.

Figure 1-16 shows four measurements of dose rate as a function of shielding depth made by IBMP on Cosmos 1887. The methodology utilized by the IBMP group in measured depth/dose profiles on Cosmos 1887 is the same as that for previous Cosmos missions. Akatov et al.[4] reports that the average dose rate for this flight in the first 100 μm of the TLD stacks was 1.4 Gy/day. The thickness of the protective cover for the TLD stacks was 1.76×10^{-3} g/cm^2.

Table 1-2. Dose measured in TLD-100, -600 and -700 detectors and differences of TLD-600 and -700 readings (values in parentheses are maximum values) measured by DLR on Cosmos 1887[7].

Experiment location	Experiment unit	Dose (μGy)			Difference TLD-600 and -700 readings (nGy)
		TLD-100	TLD-600	TLD-700	
Inside spacecraft	Type II (ESA)	3.62 ± 0.16	3.99 ± 0.18	3.58 ± 0.26	410 ± 311
		3.47 ± 0.12	3.70 ± 0.28	3.40 ± 0.15	300 ± 318
	Type II (ESA/USSR)	4.24 ± 0.19	4.16 ± 0.19	4.44 ± 0.18	280 ± 262
		3.73 ± 0.13	4.12 ± 0.23	3.63 ± 0.17	490 ± 286
	Type I (ESA)	3.85 ± 0.26	3.87 ± 0.23	3.44 ± 0.21	430 ± 311
		3.88 ± 0.19	4.09 ± 0.22	3.59 ± 0.25	500 ± 333
Outside Spacecraft	Type I (USSR)	24.5 ± 2.3 (28.1)	16.7 ± 6.2 (23.6)	28.3 ± 3.3 (31.9)	
		5.25 ± 0.33	5.2 ± 0.31	5.17 ± 0.3	
	Type I (ESA)	15.6 ± 1.7	12.0 ± 2.8	23.3 ± 2.7	
		5.49 ± 0.18	5.15 ± 0.18	4.84 ± 0.2	
	Add I	33.2 ± 1.7	33.4 ± 1.7	30.1 ± 1.5	
	Add II	1198 ± 145 (1351)	1281 ± 175 (1471)	1254 ± 225 (1434)	

Depth/dose profiles measured by the USF group[8] on Cosmos 1887 are shown in Figures 1-17, 1-18, and 1-19. Depth dose measurements for TLD stacks 1 and 2 from Experiment K-26-25 Container F1 are shown in Figure 1-17. The stacks were composed of thin TLDs (9.14×10^{-3} cm) up to ~1 g/cm^2 and thick (0.889 mm) TLDs in the remainder of the stack. A double layer of aluminized Kapton foil totaling 15 μm (2.16×10^{-3} g/cm^2) covered the stacks. Figure 1-18 shows similar depth/dose measurements made in TLD stacks 1 and 2 from Experiment K-6-25, container F2. The scatter in the data from stacks containing thin TLDs is due to the imprecise vertical alignment of the smaller TLD chips. Experiment configuration was identical to that in Container F1. Figure 1-19 shows depth/dose profiles measured using thick (0.889 mm) TLDs in stack 3 from Experiment K-6-25, Containers F1 and F2. A double layer of aluminized Kapton foil totaling 15 μm (2.16×10^{-3} g/cm^2) covered the stacks. Table 1-3 summarizes the dose rates as a function of depth for the USF dose measurements made on Cosmos 1887.

Figure 1-20 shows a comparison of depth/dose profiles made by IBMP and USF on the exterior of Cosmos 1887[9]. Also shown is a model calculation for this shielding geometry made using the AP-8MIN trapped proton and AE-8MIN trapped electron models. There is fairly good agreement between all three curves although the IBMP curve is consistently lower than the USF curve.

Table 1-3. USF TLD dose rats as a function of shielding depth on Cosmos 1887[8].

Detector	TLD Stacks	Depth in ^{7}LiF (g/cm2)*	Tissue-Absorbed Dose Rate (cGy/day)
K-6-25 F1	1 + 2	0.012	264
K-6-25 F2	1 + 2	0.012	161
K-6-25 F1	1 + 2	0.1	5.3
K-6-25 F2	1 + 2	0.1	4.4
K-6-25 F1	1 + 2	0.5	0.40
K-6-25 F2	1 + 2	0.5	0.29
K-6-25 F1	1 + 2	1.0	0.13
K-6-25 F2	1 + 2	1.0	0.076
K-6-25 F1	3	1.0	0.17
K-6-25 F2	3	1.0	0.13
K-6-25 F1	1 + 2	2.0	0.049
K-6-25 F2	1 + 2	2.0	0.038
K-6-25 F1	3	2.0	0.060
K-6-25 F2	3	2.0	0.046
K-6-25 F1	1 + 2	3.4	0.038
K-6-25 F2	1 + 2	3.4	0.028
K-6-25 F1	3	3.4	0.040
K-6-25 F2	3	3.4	0.032
K-26-24		Inside Spacecraft	0.0248 ± 0.0010

*plus 2.16 ± 10^{-3} g/cm^2 Kapton

1.2.5 Cosmos 2044

Like Cosmos 1887, Cosmos 2044 carried a large number of external experiments from a number of different research groups. The 'waffle iron' containers were again used to make depth/dose measurements on the external surface of the spacecraft. Cosmos 2044 flew from 15 September to 29 September 1989 for a mission duration of 14.0 days. The

Cosmos 2044 orbit was at 82.3° inclination and had an apogee of 294 km and a perigee of 216 km.

The Institute of Radiation Dosimetry, Prague, Czechoslovakia, flew four types of TLD stacks, (a) $CaSO_4$:Dy/teflon pellets of 0.4 mm thickness manufactured by Teledyne Isotopes, (b) $CaSO_4$:Dy/Si rubber of 0.32 mm thickness, (c) aluminophosphate (Al-P) glass TLDs of Czech manufacture ranging in thickness from 0.35 to 1 mm thickness and (d) Al-P TLDs of Russian manufacture also ranging in thickness from 0.35 to 1 mm in thickness. The TLD stacks were mounted in Al holders of the type used by Schmidt et al.[6] on Cosmos 1887. Figure 1-21 shows the four sets of depth/dose profiles measured in Container B9-3 on Cosmos 2044. Figure 1-22 shows the four sets of depth/dose profiles measured in Container B9-4 on Cosmos 2044. Only one data point is available for the $CaSO_4$:Dy/teflon stack in B9-3 because of melting of the stack during reentry. This was caused by improper closure of the B9-3 container prior to deorbit. The other depth/dose profiles from B9-3 were thus also exposed to excessive heating, leading to unreliability in the data. No such problem was encountered for Container B9-4.

The USF group measured depth/dose profiles using stacks of ^{7}LiF TLDs in four external 'waffle iron' containers. This data is presented in Figure 1-23. The experimental configuration of the USF stacks was identical to that used in the Cosmos 1887 experiments and there is consistent agreement between all four curves. This is despite the fact the curve B9-3 is from a container that did not fully close during reentry while the other three containers were fully closed. A summary of dose and dose equivalent rates calculated for Cosmos 2044 by Watts[11] is presented in Table 1-4. This data represents minimum and maximum dose rate and dose equivalent rate values both inside and outside the Cosmos 2044 satellite from trapped protons and trapped electron models.

Table 1-4. Calculated values of the absorbed dose (D) and dose equivalent (H) dose rates in the Cosmos 2044 orbit[11].

	Detectors mounted			
	Outside satellite		Inside satellite	
Version	D (mrad/day)	H (mrem/day)	D (mrad/day)	H (mrem/day)
Maximum	9.7	25.9	5.6	12.5
Minimum	7.6	13.6	4.0	5.1
Mean Doses	8.6 ± 1.4	19.7 ± 6.2	4.8 ± 0.8	8.8 ± 3.7

The DLR group of Reitz et al.[12] also carried out measurements of dose as a function of shielding depth on Cosmos 2044 similar to those carried out by the DLR group on Cosmos 1887. Depth/dose was measured in one container labeled Add 3 as well as in two locations labeled Dos 2 and Dos 3. These results may be found in Figure 1-15 along with the results of depth/dose measurements made by Reitz et al. on Cosmos 1887. Table 1-5 summarized dose measurements made inside and outside the Cosmos 2044 satellite by Reitz using TLD-600.

Table 1-5. Doses measured with TLD 600 detectors in the interior and exterior of the Cosmos 2044 by DLR[12].

Experiment Location	Experiment Unit	Dose (mGy)
Inside Spacecraft	Carausius I	2.8 ± 0.1
		2.5 ± 0.1
	Carausius II	5.8 ± 0.6
		3.7 ± 0.6
	Carausius III	2.6 ± 0.2
		2.5 ± 0.2
	Dos 1	4.4 ± 0.2
		3.7 ± 0.3
	Dos 2	4.6 ± 0.4
		4.2 ± 0.4
Outside Spacecraft	Dos 3	1.6 ± 0.1
	Dos 4	1.7 ± 0.1

1.2.6 STS-46 and Photon 8

Depth dose measurments were made on the STS-46 mission in the Space Shuttle cargo bay as part of the EIOM3 experiment. STS-46 was a low inclination (28.5°) mission lasting 7.97 days. The maximum altitude was 520 km while the minimum altitude was 420 km. The results can be seen in Figure 1-24[13]. The EIOM3 depth/dose profile is the only measurement of dose as a function of shielding under thin shielding for a low inclination orbit. The most recent depth/dose profile data available is from the Russian Photon 8 recoverable satellite also carried out by the USF group. Results may be found in Figure 1-25[14]. Photon 8 was a 15.6 day mission in a 62.8° inclination orbit. Apogee was 359 km while perigee was 220 km. The experiment configuration for the Mir, EIOM3 and Photon 8 measurements was similar to that used by the USF group on the Cosmos 1887 and 2044 missions.

1.2.7 External Dose Measurements on Mir

Dose rate was measured as a function of shielding depth aboard the Russian Mir Space Station on two separate occasions using stacks of thin TLD-700 detectors mounted on the external surface of the Kvant 2. Stacks of thin (0.0036") and regular (0.035") TLDs were mounted inside Lexan holders which were in turn mounted inside specially designed aluminum blocks. The aluminum blocks were in turn mounted on a removable aluminum tray (pictured in Figure 1-26). The removable tray, referred to as the External Dosimeter Array (EDA) also contained similar thin TLD stacks from the Institute of Biomedical Problems (IBMP) in Moscow and several sets of plastic nuclear track detectors (PNTD) from both USF and IBMP. The EDA was stored inside the Mir station before and after external exposure. It was deployed during an EVA and mounted in the specially designed STD platform on the outside surface of the Kvant 2 module. The STD platform is mounted above two gyrodynes as pictured in Figure 3-2. It is partially blocked by a solar array attached to the Mir Base Block. While the EDA tray was of the same design during both experiments, the composition and arrangement of passive detectors and their holders differed between the two exposures. The original EDA used during the June 1991 experiment was never returned to Earth, and no drawings or photographs of the original experiment could be located. Thus there are probably small differences in shielding between the two exposures. Differences in the two exposures also arise from the fact that the Mir only possessed the Base Block, Kvant 1, Kvant 2 and Kristall modules during the 1991 exposure. By 1997, the Spektr and Priroda modules had been added and the arrangement of the older modules was modified to accommodate the newer ones. In addition, it is possible that the station orientation was different for the two exposure times. These measurements were as nearly as possible carried out under identical conditions except for solar epoch. Duration of the exposures, time spent inside Mir both before and after exposure, etc. were beyond the control of the P.I.

The first measurement was made in June 1991, roughly corresponding to Solar Maximum. This set of exposures lasted approximately 27 days. The second set of measurements was carried out beginning on 29 April 1997 and ending on 5 September 1997, a period roughly corresponding to Solar Minimum. Total duration of the second set of exposure is was 130 days. Figure 1-27 shows dose rate as a function of shielding depth in TLD-700[15]. As expected, the measurements made at solar maximum lie well above the measurements made during solar minimum. At greater shielding depth (above 1 g/cm^2) the two sets of measurements begin to level off and intersect, due to the fact that shielding from the sides of the stack is now of the same magnitude as the shielding from above. Differences in shielding between the two experiments, especially shielding immediately surrounding that stacks, most likely account for the differences in shape between the two sets of measurements.

A calculation for the June 1991 measurement was made using the AP8MAX trapped proton and AE8MAX trapped electron models[16]. This curve also lies well below the June 1991 measured curves. The large magnitude of the June 1991 measurements can be attributed to the short-lived trapped belts produced from the October 1989 Solar Particle Events. Calculation for the 1997 measurements have yet to be carried out, but since these exposures were made during a period near Solar Minimum and there were no significant SPEs during this time, agreement between measurements and calculations is expected to be better.

1.3 DISCUSSION OF EXTERNAL DOSE MEASUREMENTS

All the measurements of dose rate as a function of shielding depth reported herein share the same characteristic rapid drop in dose rate within the first g/cm^2 of shielding. This is caused by the attenuation of low energy electrons within the outermost layers of shielding. Between ~0.01 and 1 g/cm^2, dose rate falls off by between two and four orders of magnitude. Low energy electrons dominate this region while above 1 g/cm^2 they make little contribution to absorbed dose rate. At greater shielding depths, dose rate is dominated by higher energy protons and electrons. Low energy electrons are mostly encountered near the geomagnetic poles, making their contribution to the exposure of high inclination Biocosmos missions quite significant.

Figure 1-28 shows dose rate as a function of depth for two 62.8° inclination missions: Cosmos 1887 and Photon 8. Cosmos 1887 flew in 1987 close to solar minimum while Photon 8 flew in 1992 close to solar maximum. Despite this difference in solar cycle, there is close agreement between depth/dose measurements between the two missions. In fact there is larger variation between depth/dose profiles measured by different groups on Cosmos 1887 and with model calculations than between the depth/dose profiles measured on Cosmos 1887 and Photon 8 by the USF group.

Figure 1-29 shows dose rate as a function of shielding for three Cosmos mission of 70° inclination: Cosmos 1571, Cosmos 1760, and Cosmos 1781. All three sets of data were measured using Al-P glass TLDs from IBMP. The three Cosmos missions few in the 1984-1986 period near solar minimum and occupied orbits of comparable apogee and perigee. Despite these similarities there is some major differences in the measured depth/dose curves for these three missions. At low shielding (~10^{-2} g/cm^2) the dose rate differs nearly an order of magnitude between the three curves. At ~1 g/cm^2 the spread in dose rates is between a factor of two and three. At the present time, the reasons for this variation are not known. Differences in orientation of the spacecraft, solar activity or poor reproducibility of scientific methodology might be responsible.

Figure 1-30 shows depth/dose profiles measured for two 82° inclination Cosmos missions: Cosmos 1514 and Cosmos 2044. Cosmos 1514 flew in 1983 while Cosmos 2044 flew in 1989. While the two missions shared a similar perigee of ~215 km, the Cosmos 2044 mission had an apogee of 294 km while Cosmos 1514 had an apogee of 260 km. There is good agreement between depth/dose profiles measured by different groups using different TL materials on Cosmos 2044. An exponential drop of four orders of magnitude can be seen within the first g/cm^2. Above 1 g/cm^2, dose rate levels off. This is probably due to the fact that the shielding as measured from top to bottom through the center of the stack is now comparable to the shielding from other angles such as through the sides of the stack. The two Hungarian depth/dose profiles measured on Cosmos 1514 lie well above the Cosmos 2044 curves and do not fall off as rapidly with increasing shielding. Within the first g/cm^2, the Cosmos 1514 curves only fall off by two orders of magnitude.

Figure 1-31 shows five depth/dose profiles for the different orbital inclinations for which depth/dose information is available. Inclination varies from a near polar orbit of 82.3° to a near equatorial orbit of 28.5°. The high inclination missions, Cosmos 1781 (70.4°) and Cosmos 2044 (82.3°) take the spacecraft close to the geomagnetic poles and thus increase the spacecraft's' exposure to trapped low energy electrons. This fact is borne out in the higher dose rates measured at low shielding (~ 10^{-2} g/cm^2) for the high inclination missions. The low inclination STS-46 orbit (28.5°) never gets very close to the magnetic poles but instead spends a greater fraction of time in the South Atlantic Anomaly (SAA) and is exposed to trapped protons and electrons. Consequently, the STS-46 curve is the lowest of the five plotted in Figure 1-31 and the fall off in dose rate with increasing shielding is not quite so pronounced. The variations in depth/dose profiles at higher inclinations cannot be accounted for at the present time. Variations in spacecraft orientation, solar activity, and local shielding environment might all be responsible.

Measurements of dose rate as a function of shielding under thin shielding (<1 g/cm^2) provide valuable data sets with which to compare predictions generated by radiation environment and transport codes. Caution should be taken when making such comparison since different types of TL material were used in different experiments and not all TL material register dose with the same efficiency. Differences in depth/dose profiles made by different research laboratories on the same mission can give an indication of this spread.

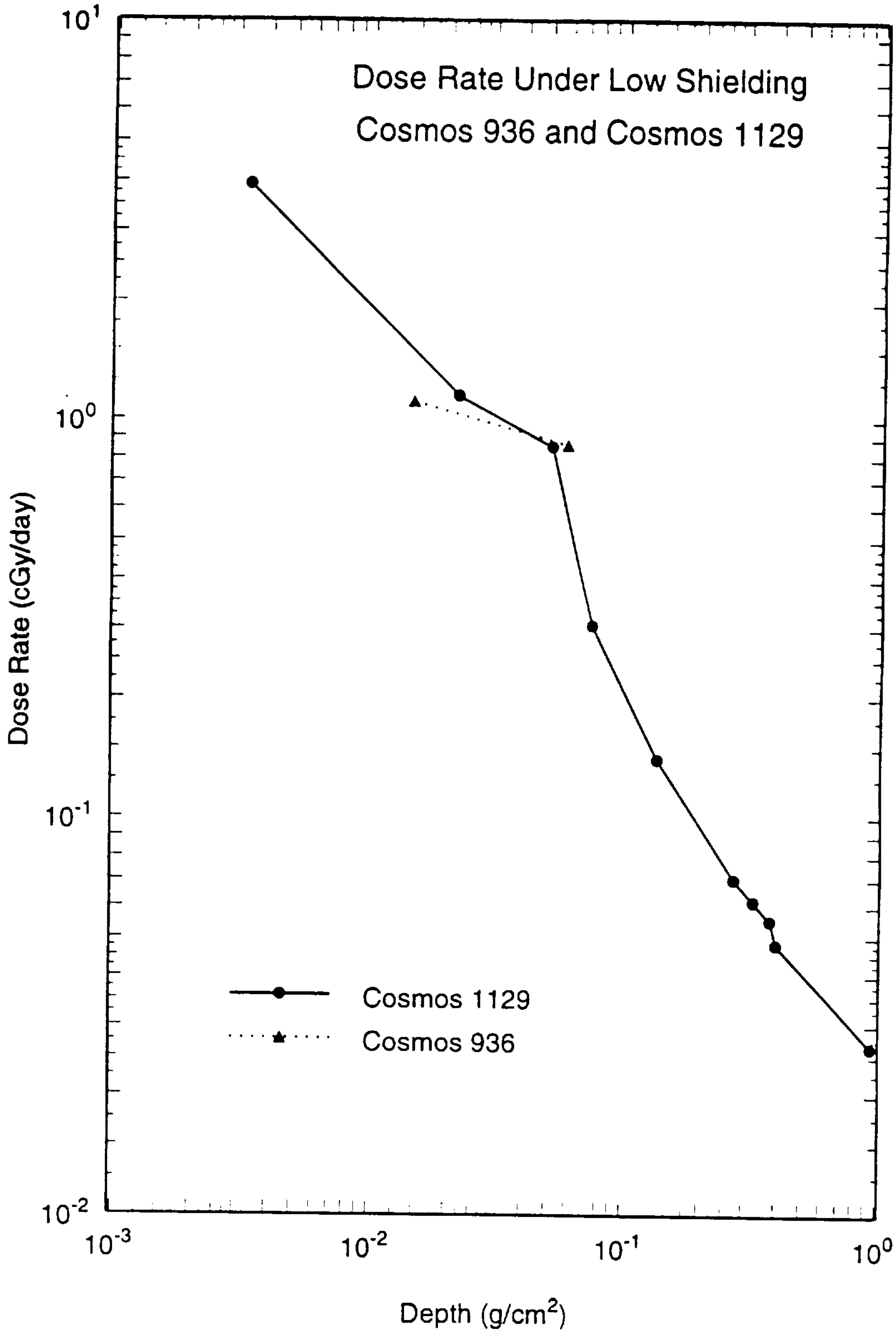


Figure 1-4. Dose rate as a function of shielding depth measured by USF on the Cosmos 936 and 1129 missions[1].

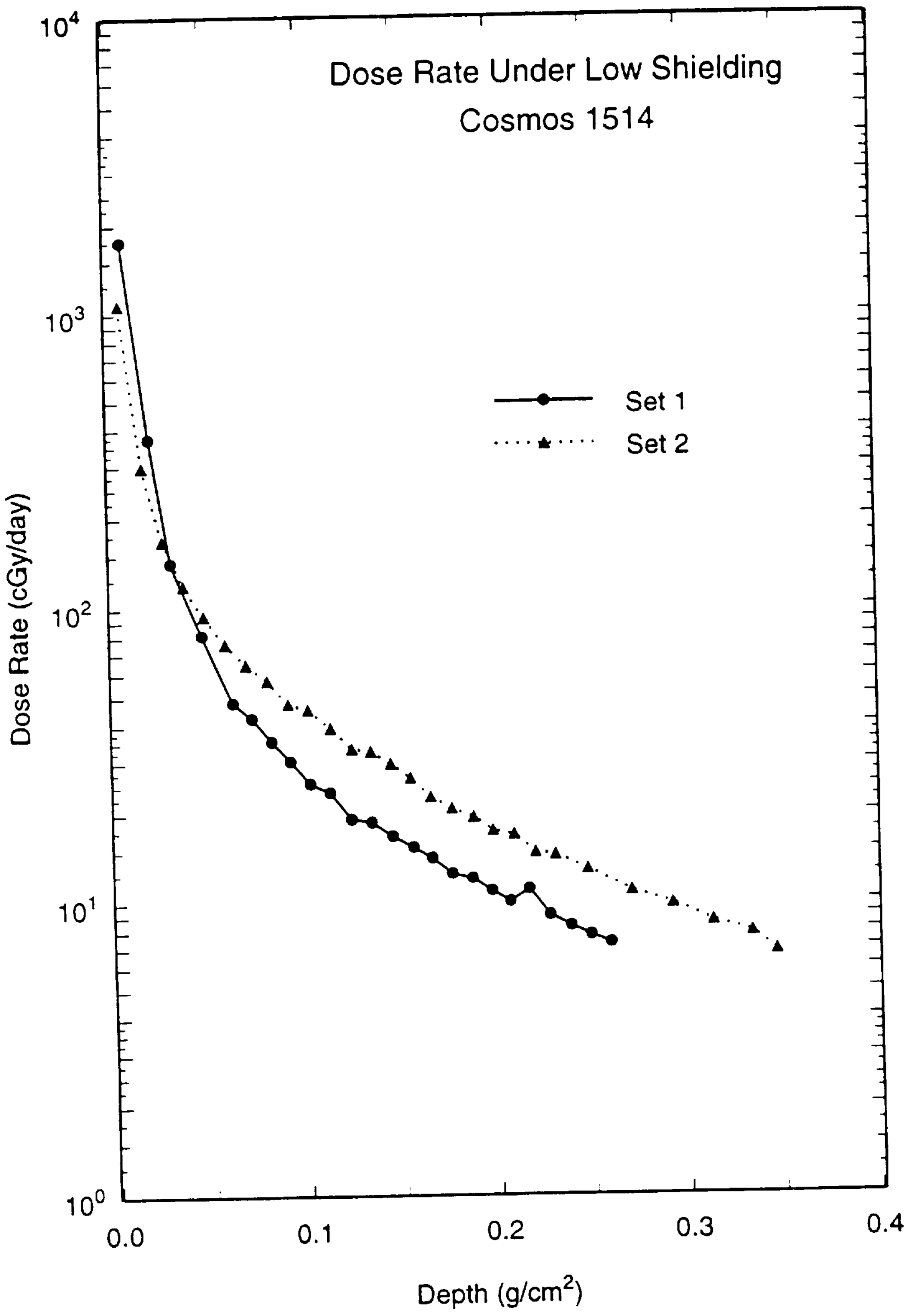


Figure 1-5. Dose rate as a function of shielding depth measured by Szabo et al. Using $CaSO_4$:Dy/Teflon rods on the Cosmos 1514 mission[2].

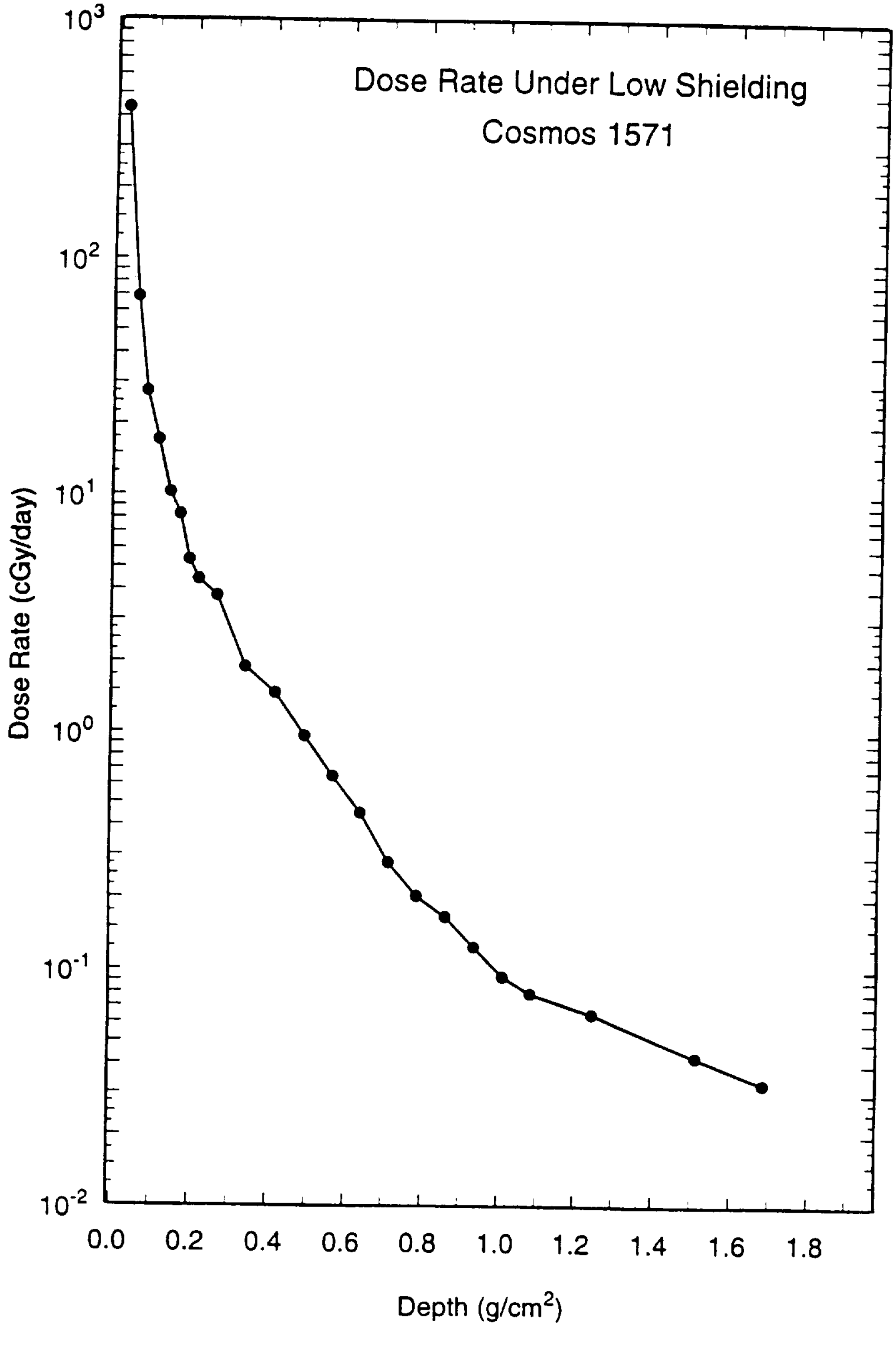


Figure 1-6. Dose rate as a function of shielding depth measured by IMBP using Al-P TLDs on Cosmos 1571[4].

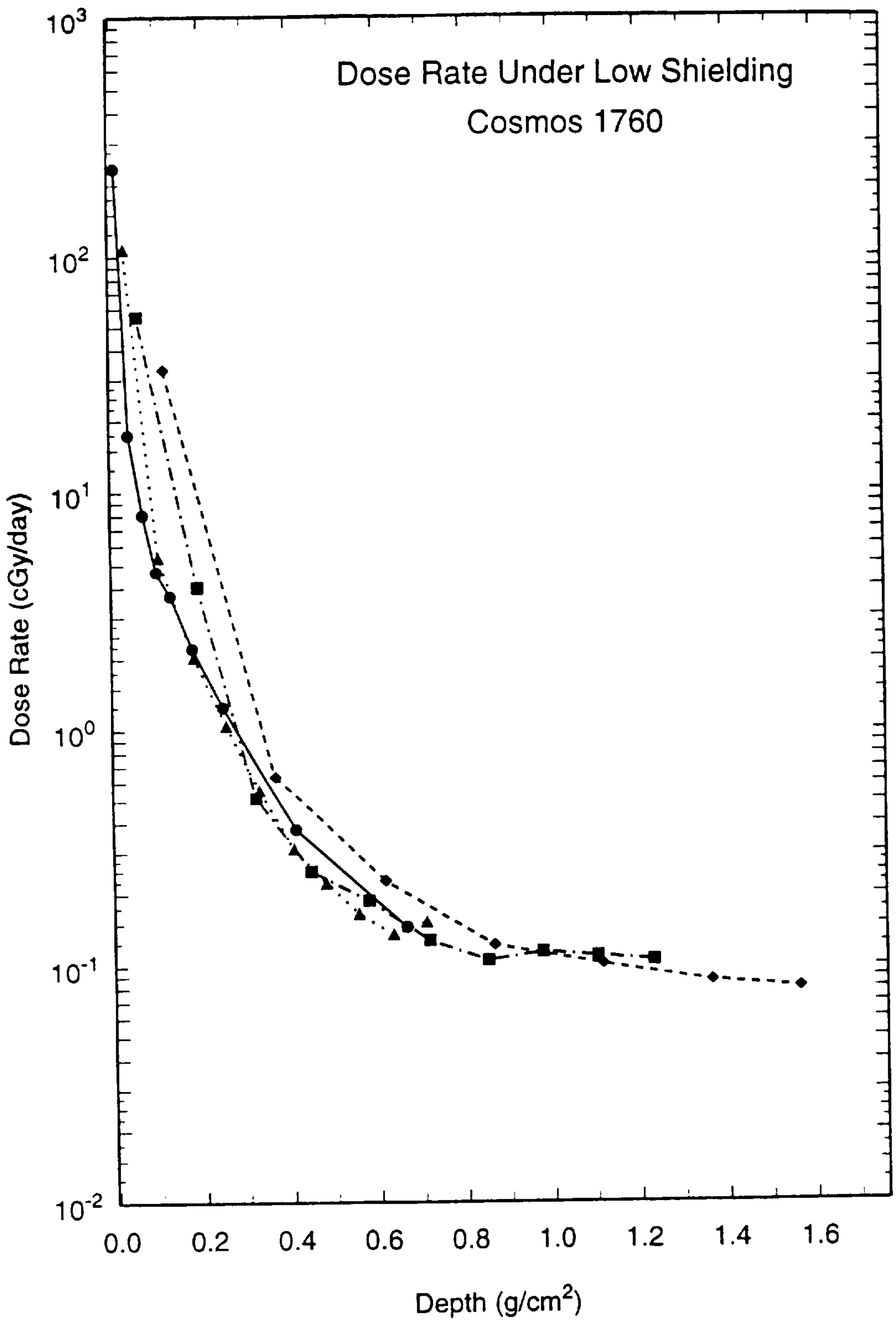


Figure 1-7. Dose rate as a function of shielding depth measured by IMBP using AL-P TLDs on Cosmos 1760[4].

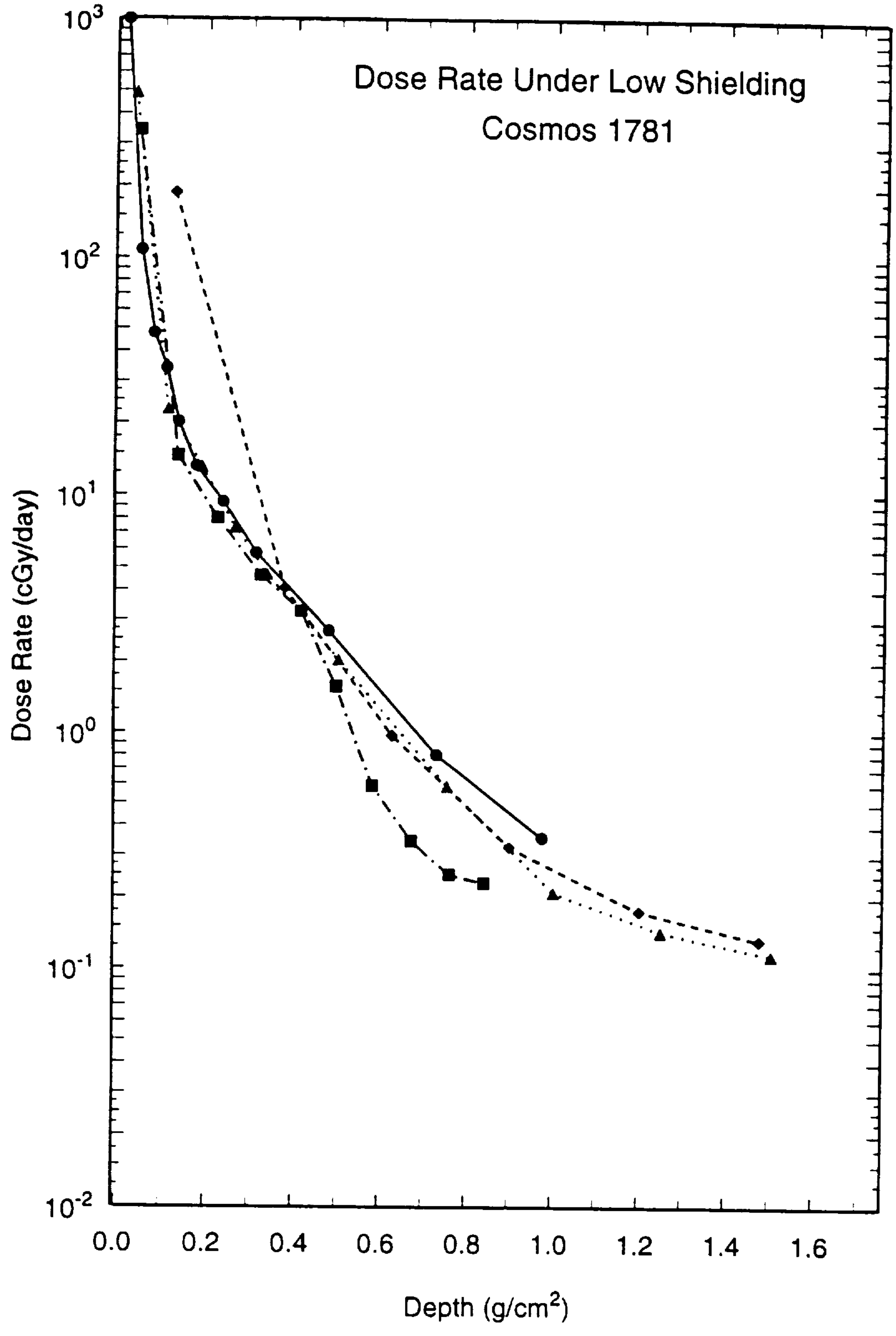


Figure 1-8. Dose rate as a function of shielding depth measured by IMBP using AL-P TLDs on Cosmos 1781[4].

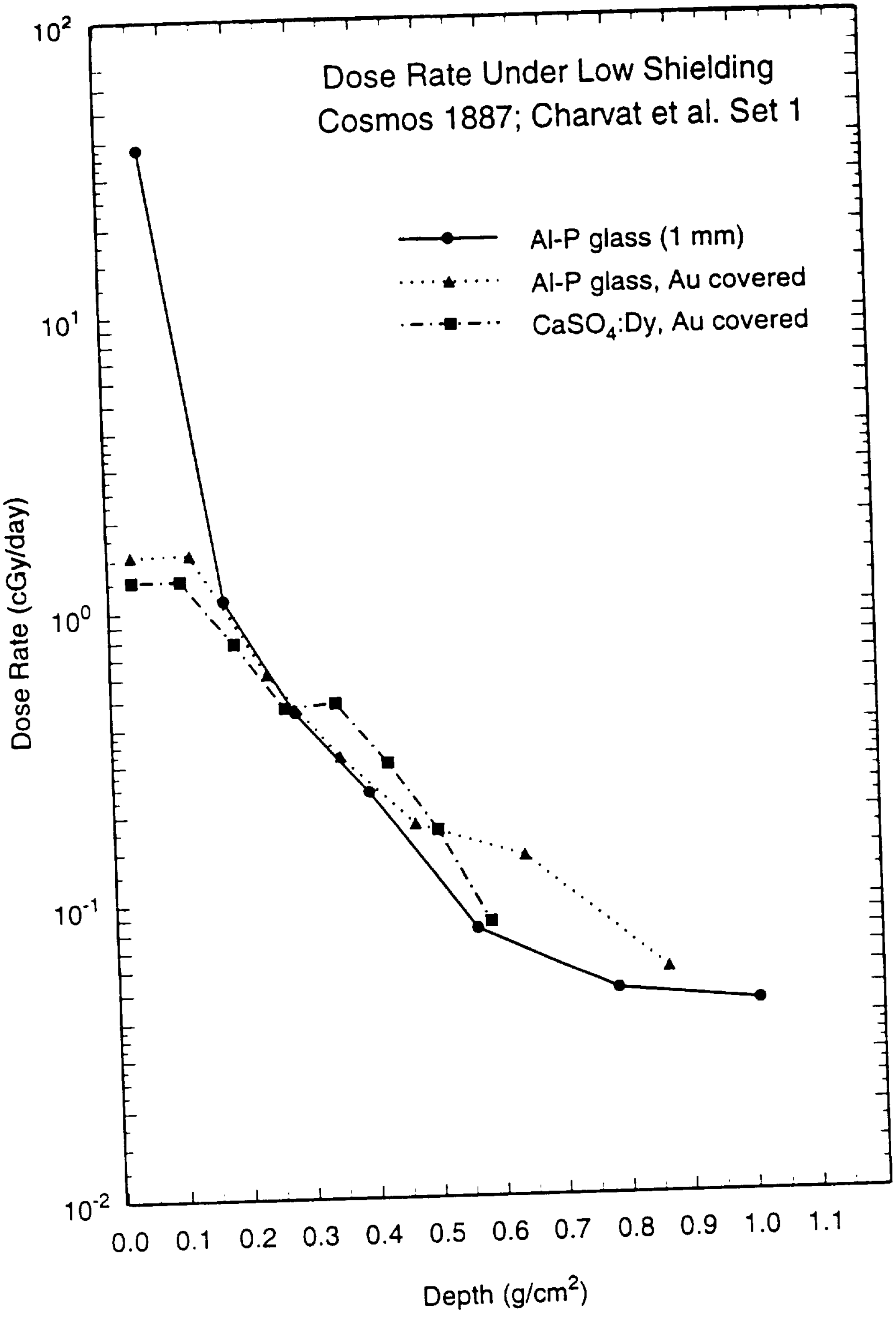


Figure 1-9. Set 1 of dose rate/shielding depth measurements carried out by Charvat et al. on Cosmos 1887[5].

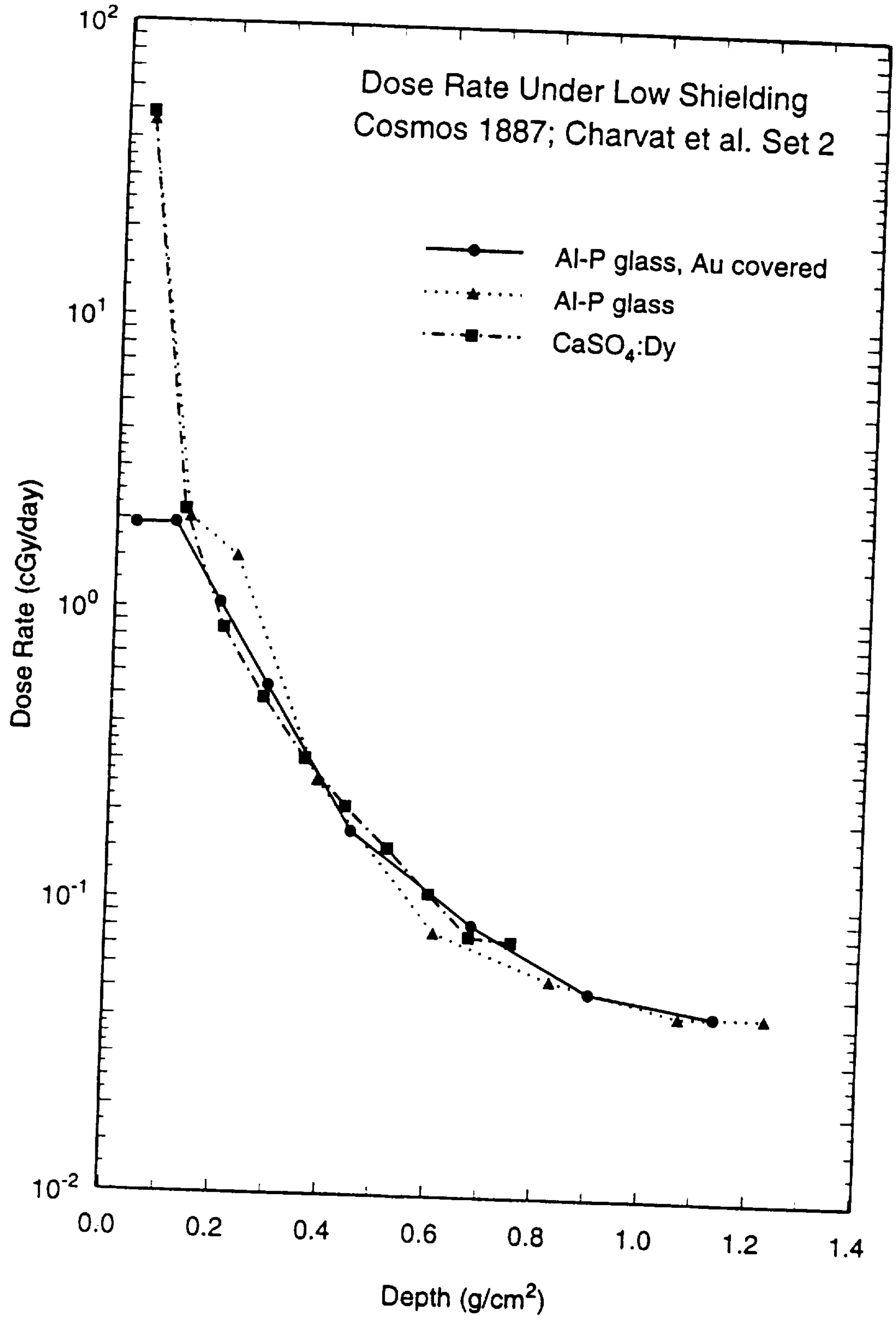


Figure 1-10. Set 2 of dose rate/shielding depth measurements carried out by Charvat et al. on Cosmos 1887[5].

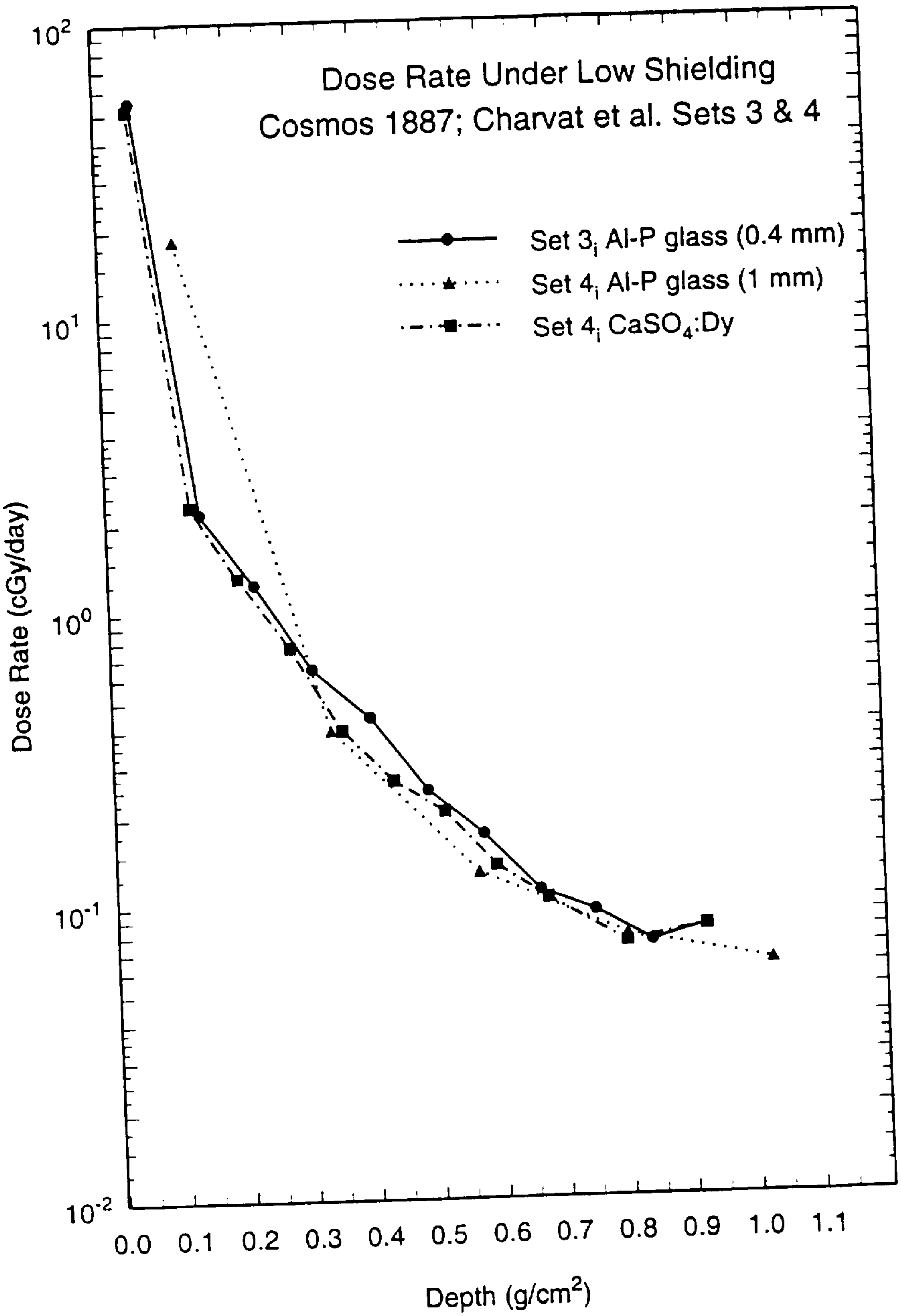


Figure 1-11. Sets 3 and 4 of dose rate/shielding depth measurements carried out by Charvat et al. on Cosmos 1887[5].

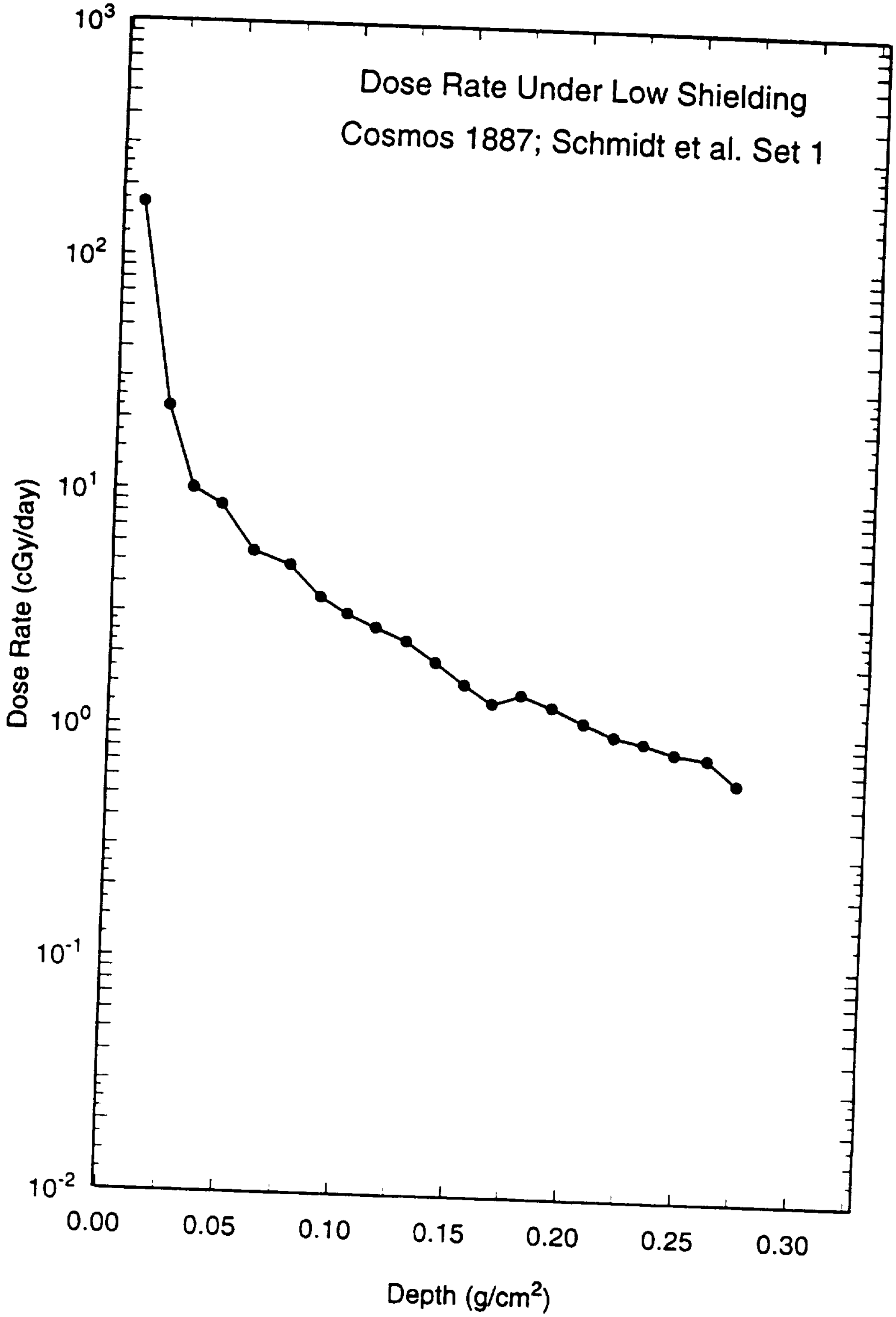


Figure 1-12. Set 1 of dose rate/shielding depth measurements carried out by Schmidt et al. on Cosmos 1887[6].

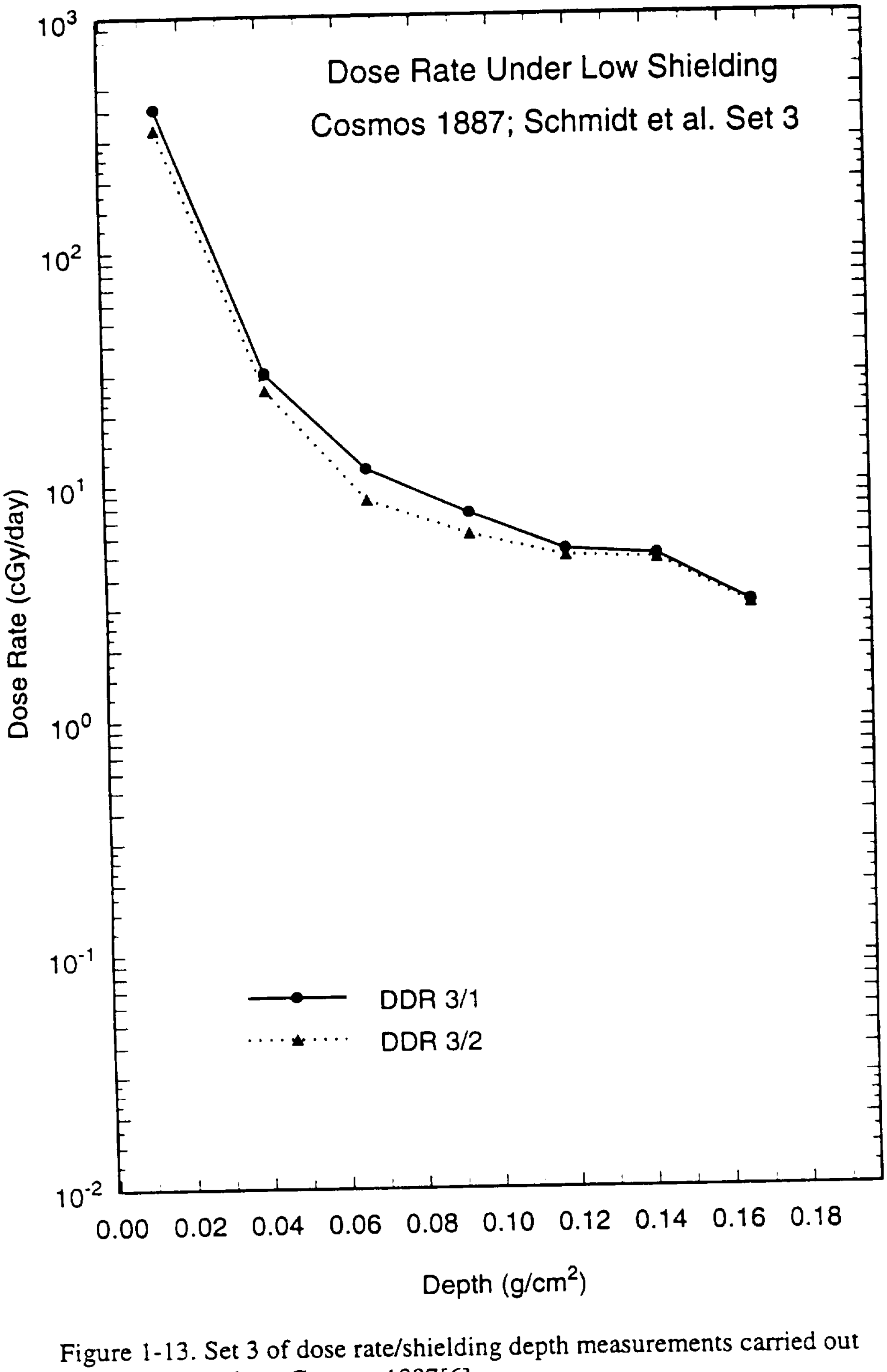


Figure 1-13. Set 3 of dose rate/shielding depth measurements carried out by Schmidt et al. on Cosmos 1887[6].

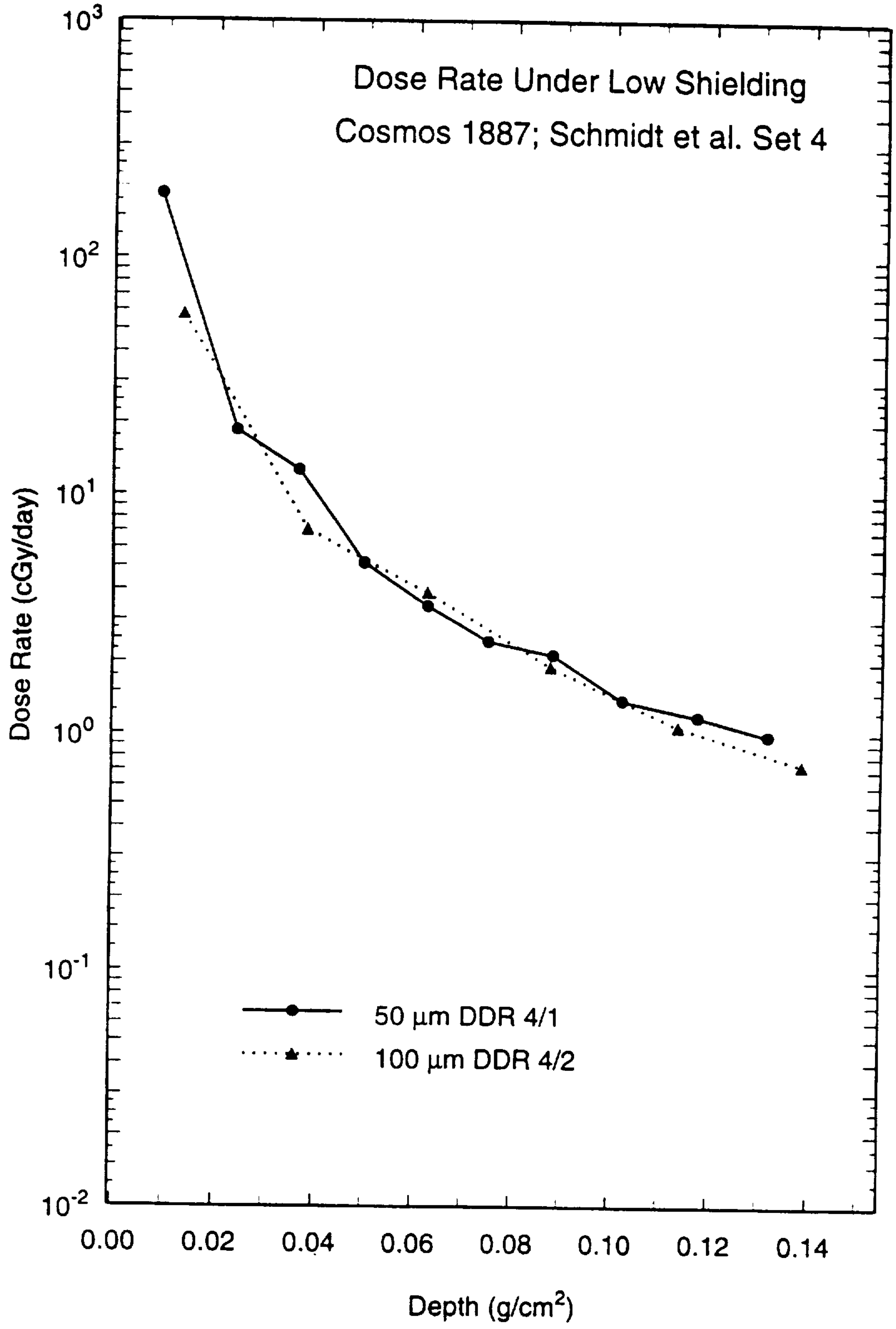


Figure 1-14. Set 4 of dose rate/shielding depth measurements carried out by Schmidt et al. on Cosmos 1887[6].

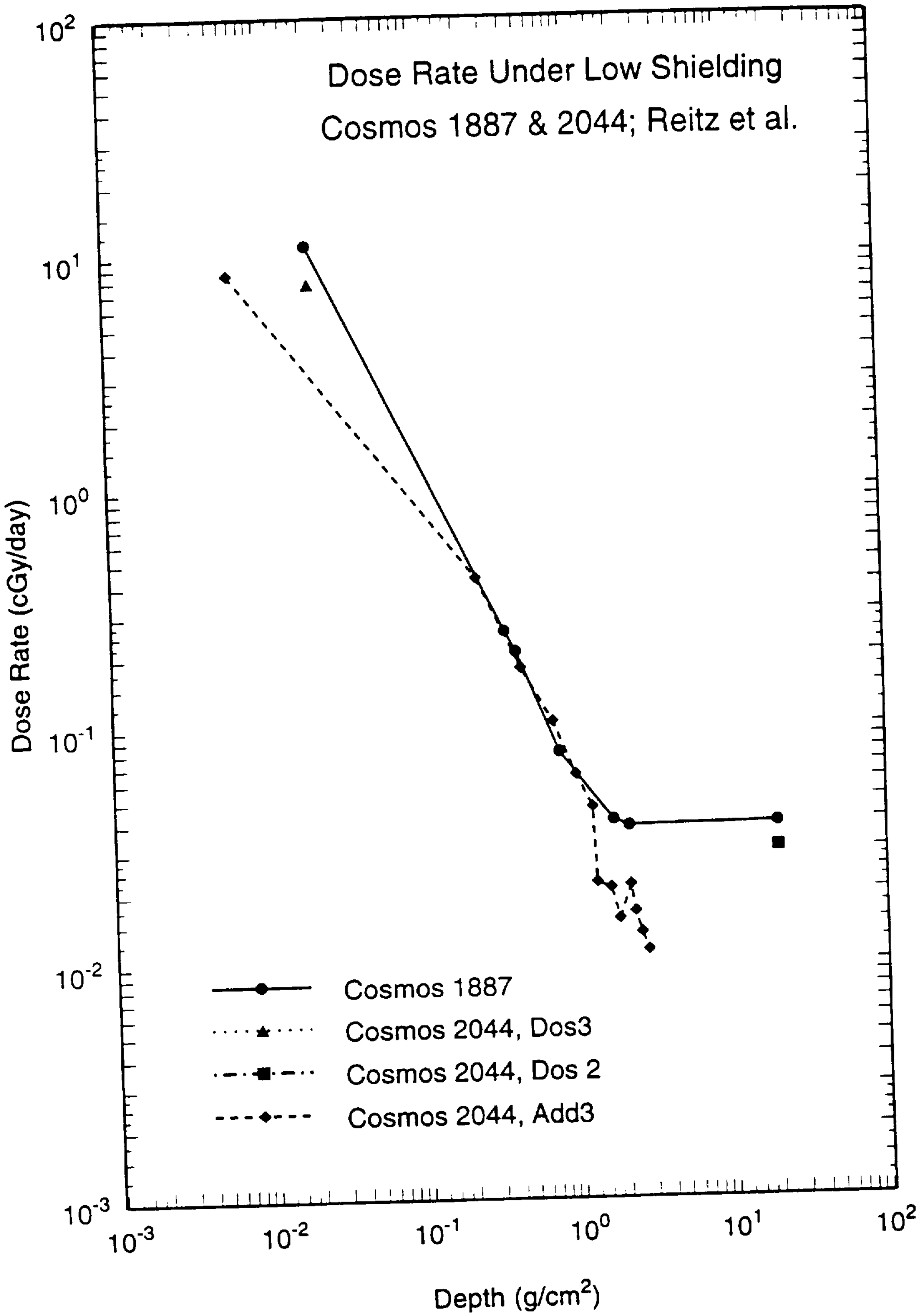


Figure 1-15. Dose rate as a function of shielding depth measured by Reitz et al. on the Cosmos 1887 and 2044 missions[7,12].

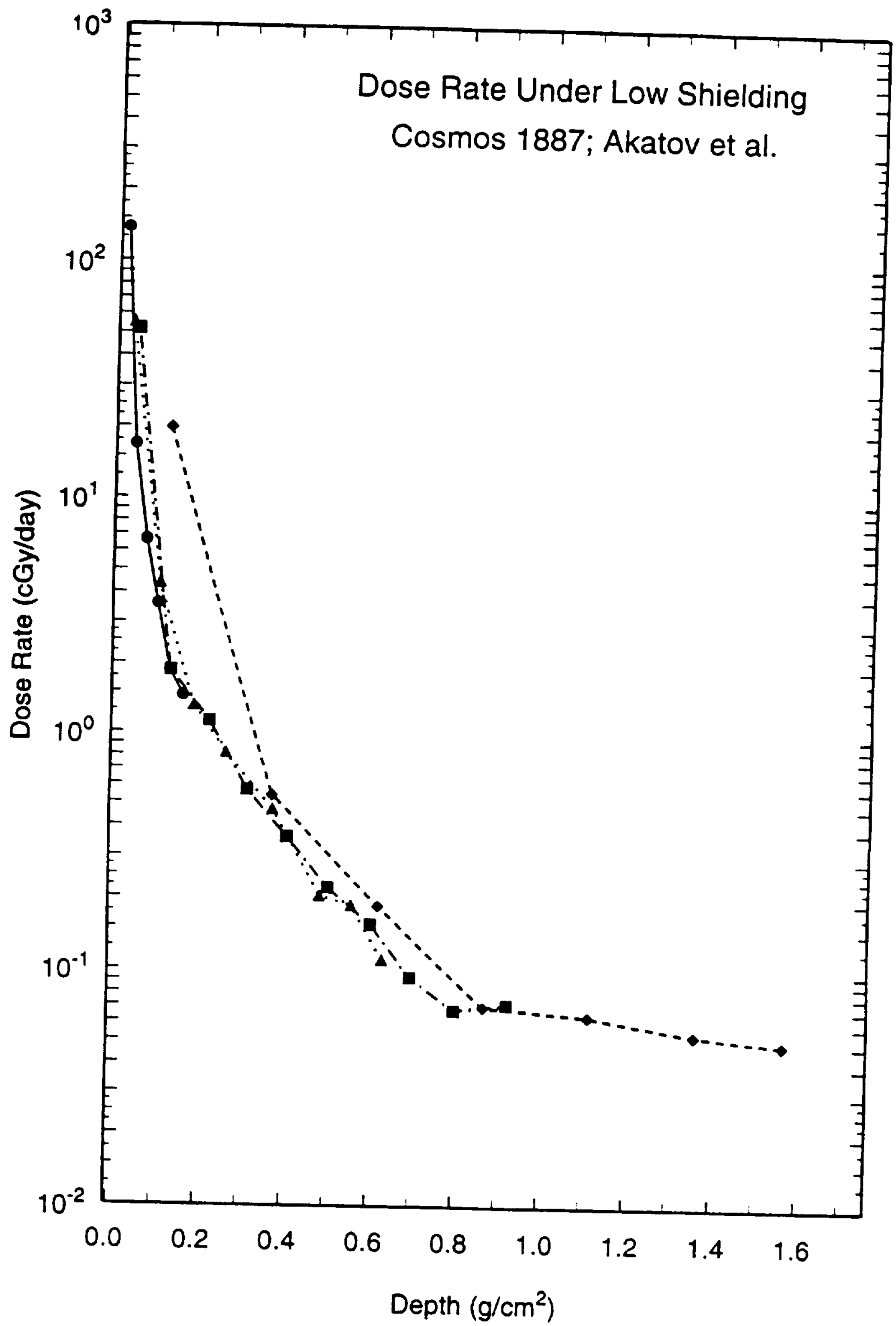


Figure 1-16. Dose rate as a function of shielding depth measured by IMBP using AL-P TLDs on Cosmos 1887[4].

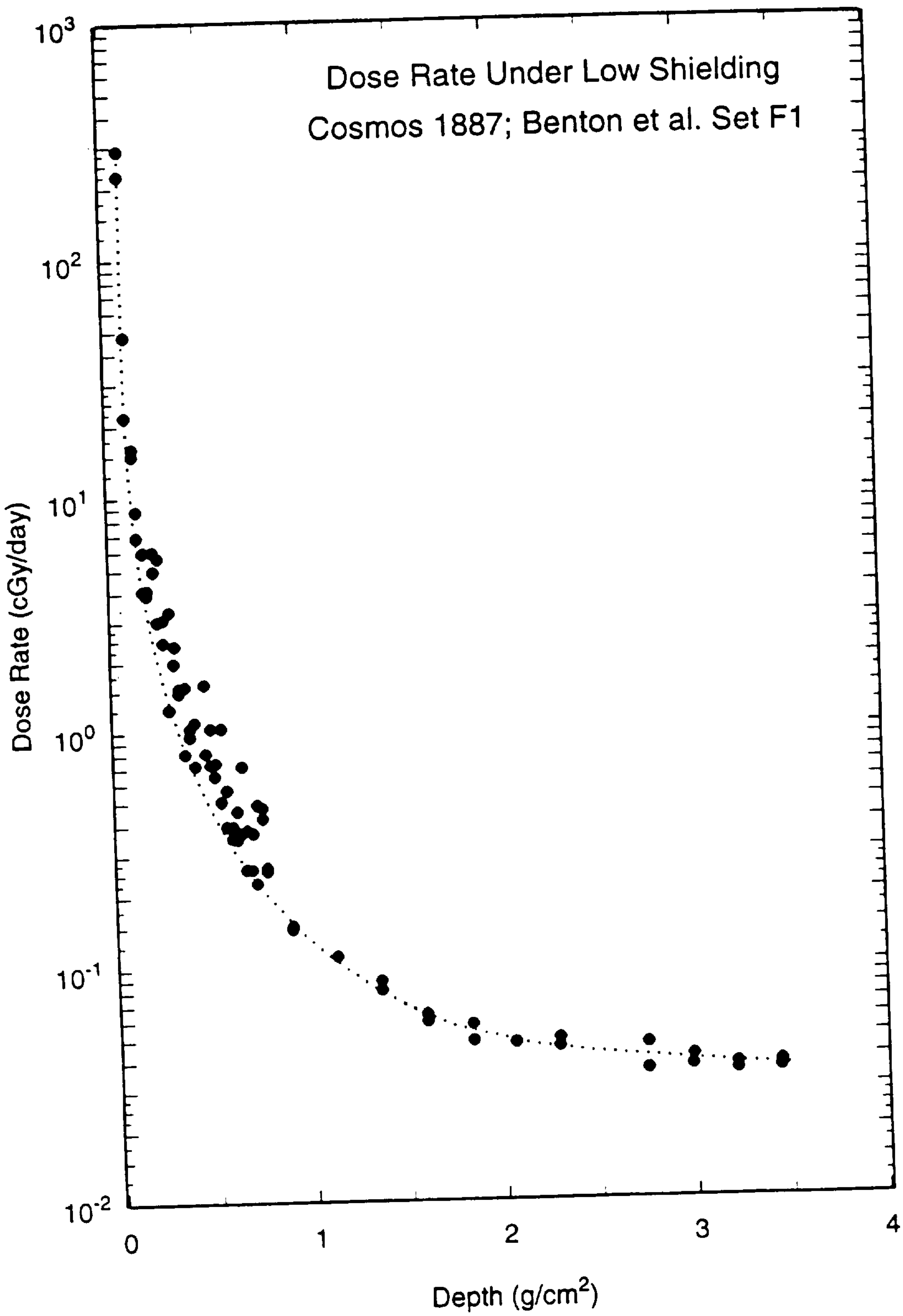


Figure 1-17. Dose rate as a function of shielding depth measured by USF in container F1 on Cosmos 1887[8].

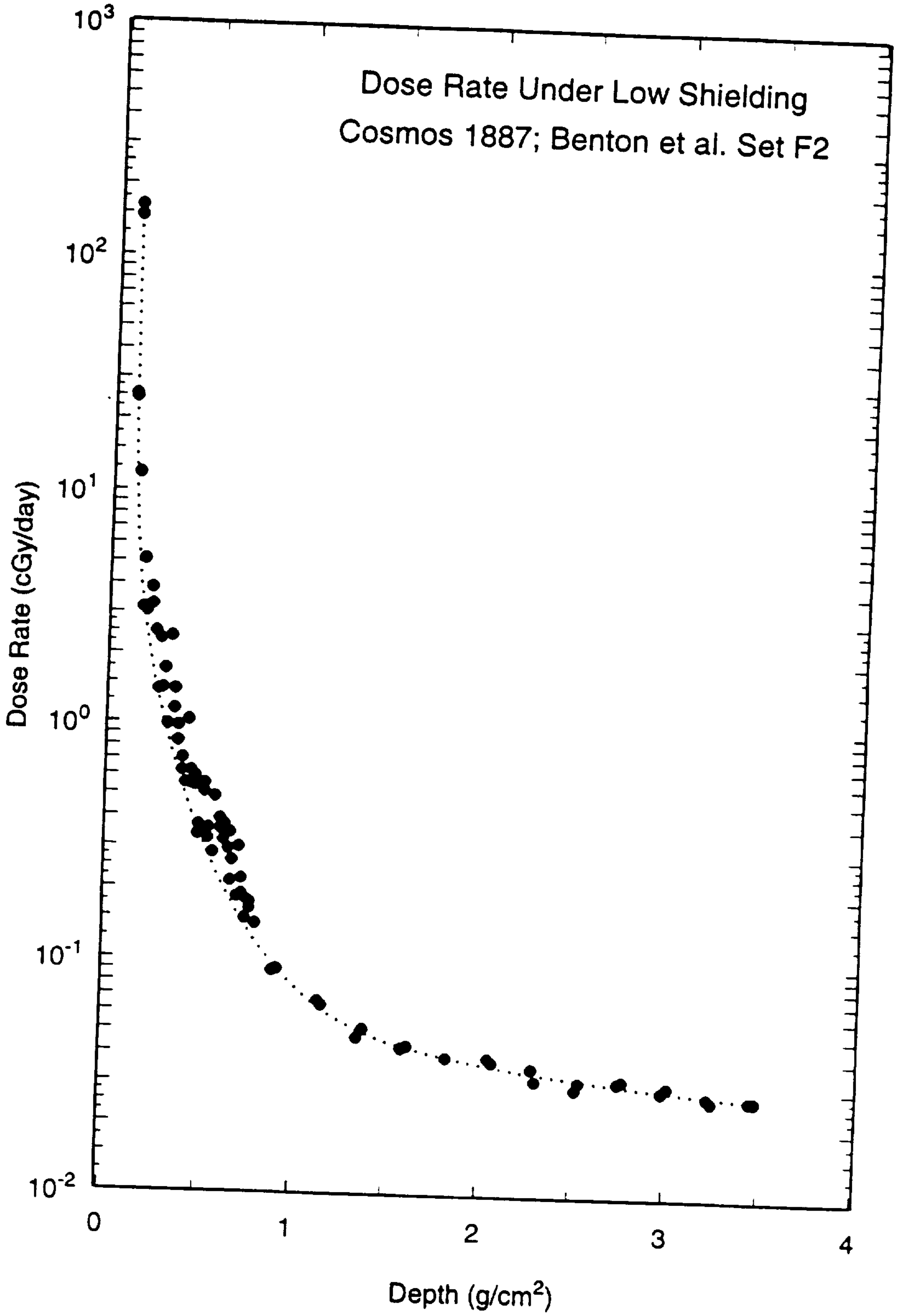


Figure 1-18. Dose rate as a function of shielding depth measured by USF in container F2 on Cosmos 1887[8].

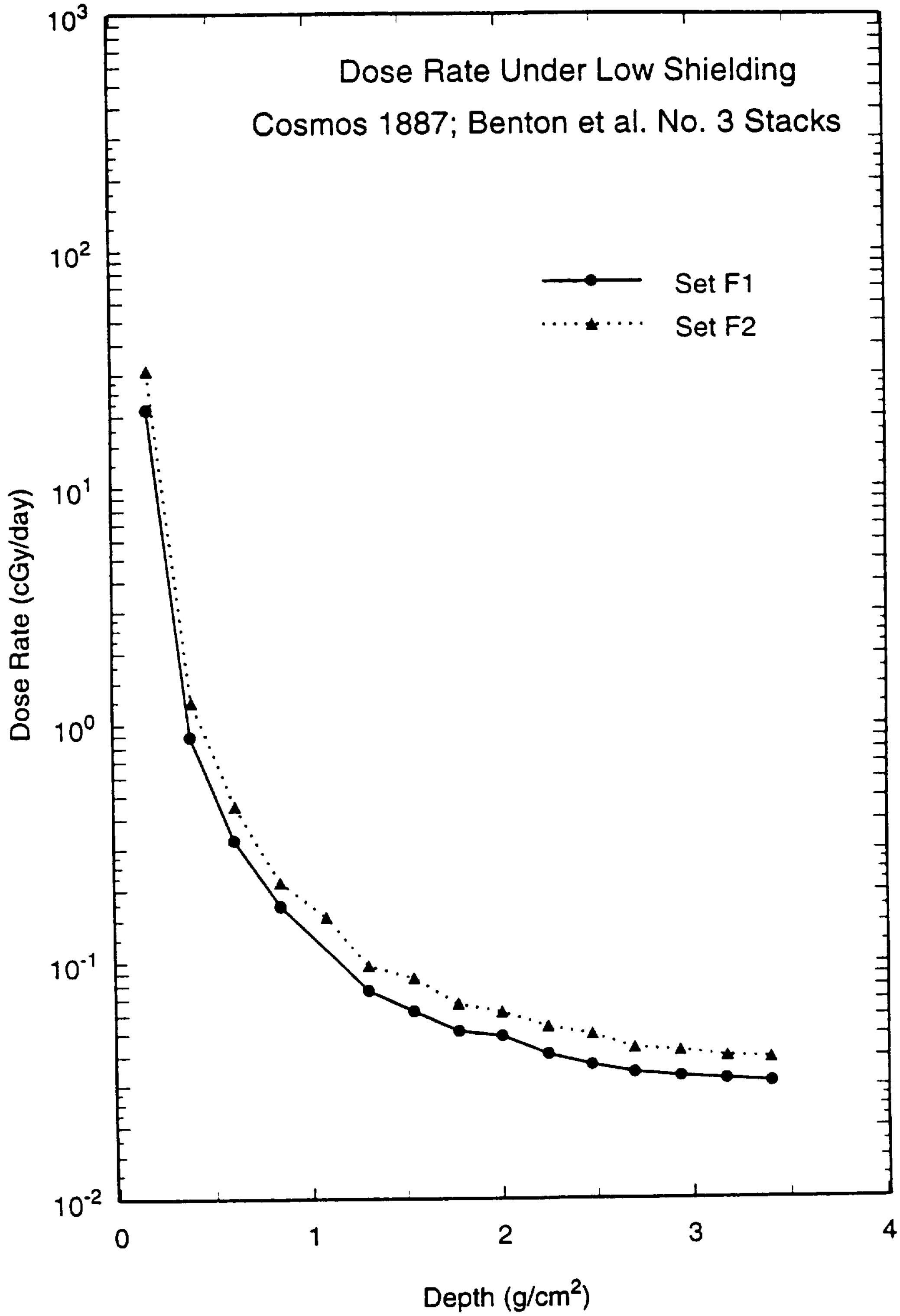


Figure 1-19. Dose rate as a function of shielding depth measured by USF in containers F1 and F2 on Cosmos 1887[8].

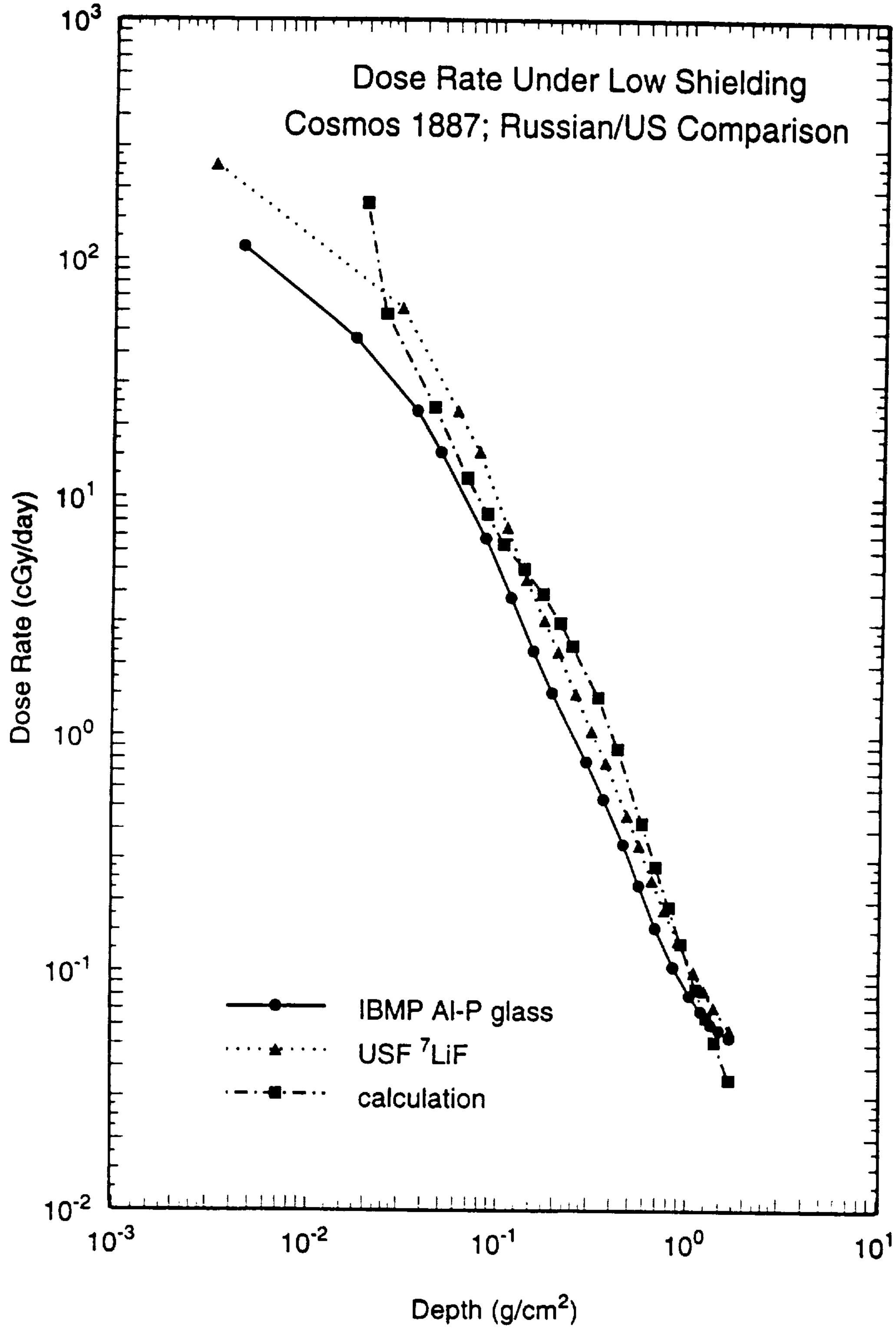


Figure 1-20. A comparison of dose rate under thin shielding measured on Cosmos 1887 by IMBP and USF and with calculation by Watts[9].

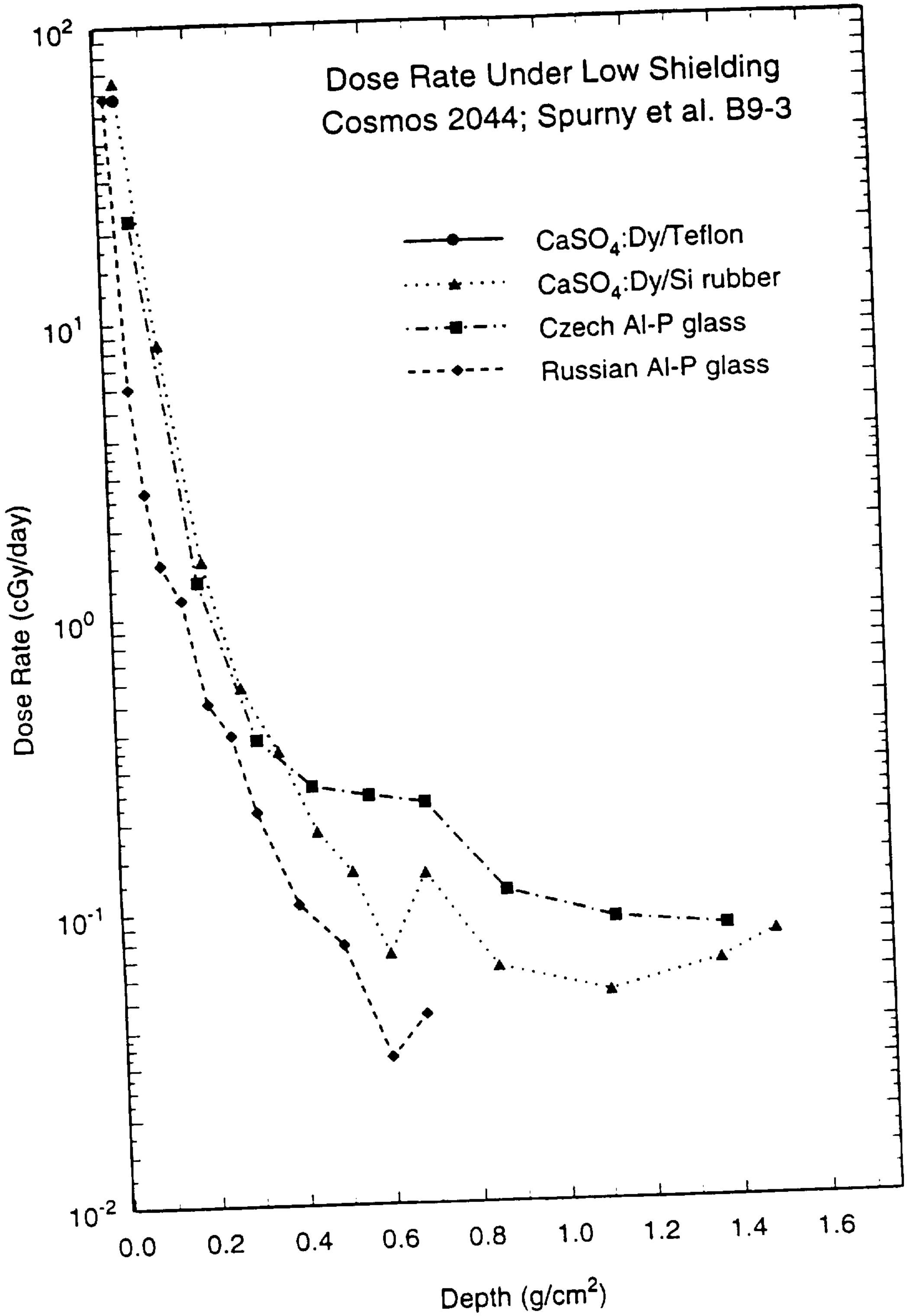


Figure 1-21. Dose rate as a function of shielding depth measured by Spurny et al. in container B9-3 on Cosmos 2044[10].

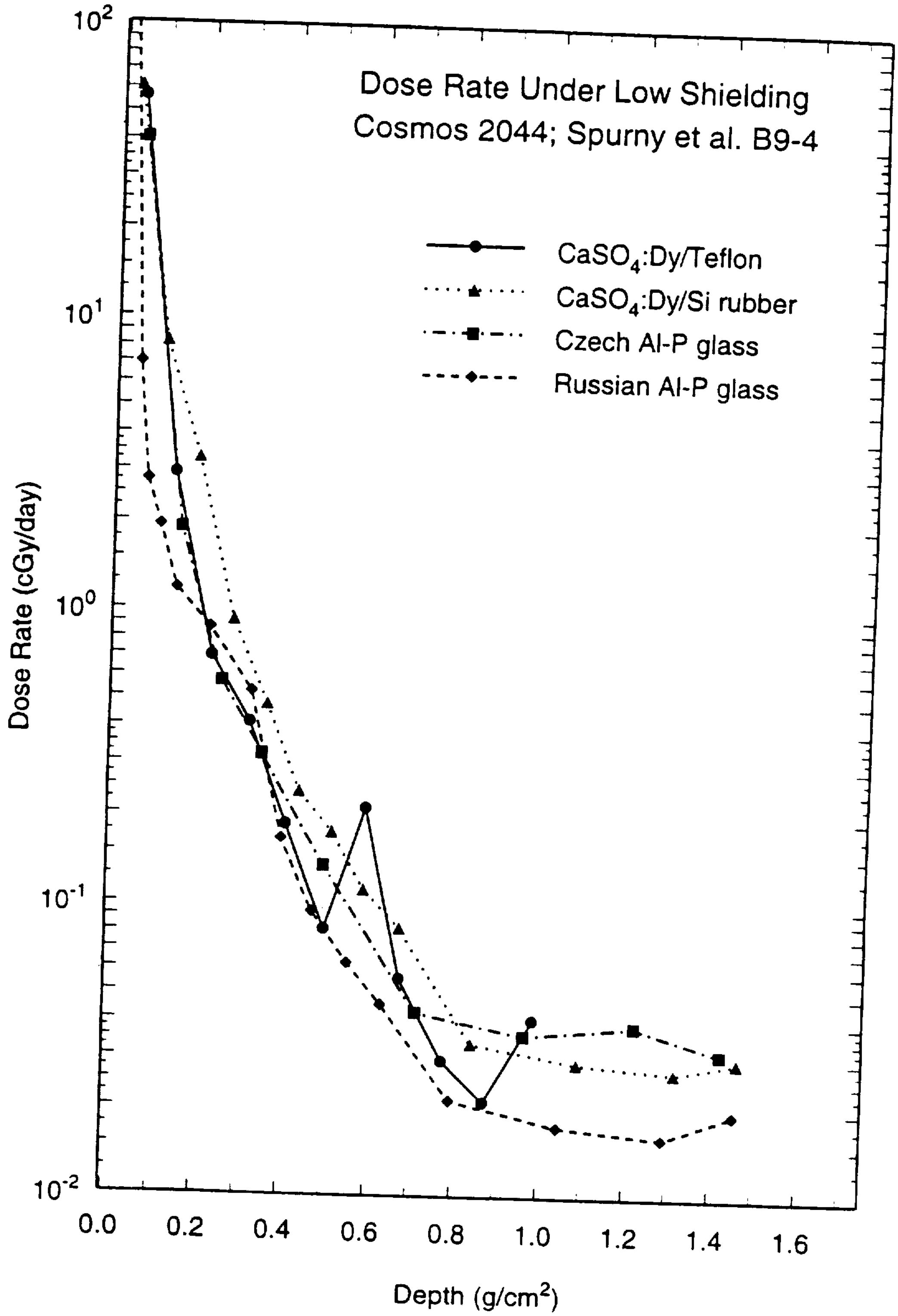


Figure 1-22. Dose rate as a function of shielding depth measured by Spurny et al. in container B9-4 on Cosmos 2044[10].

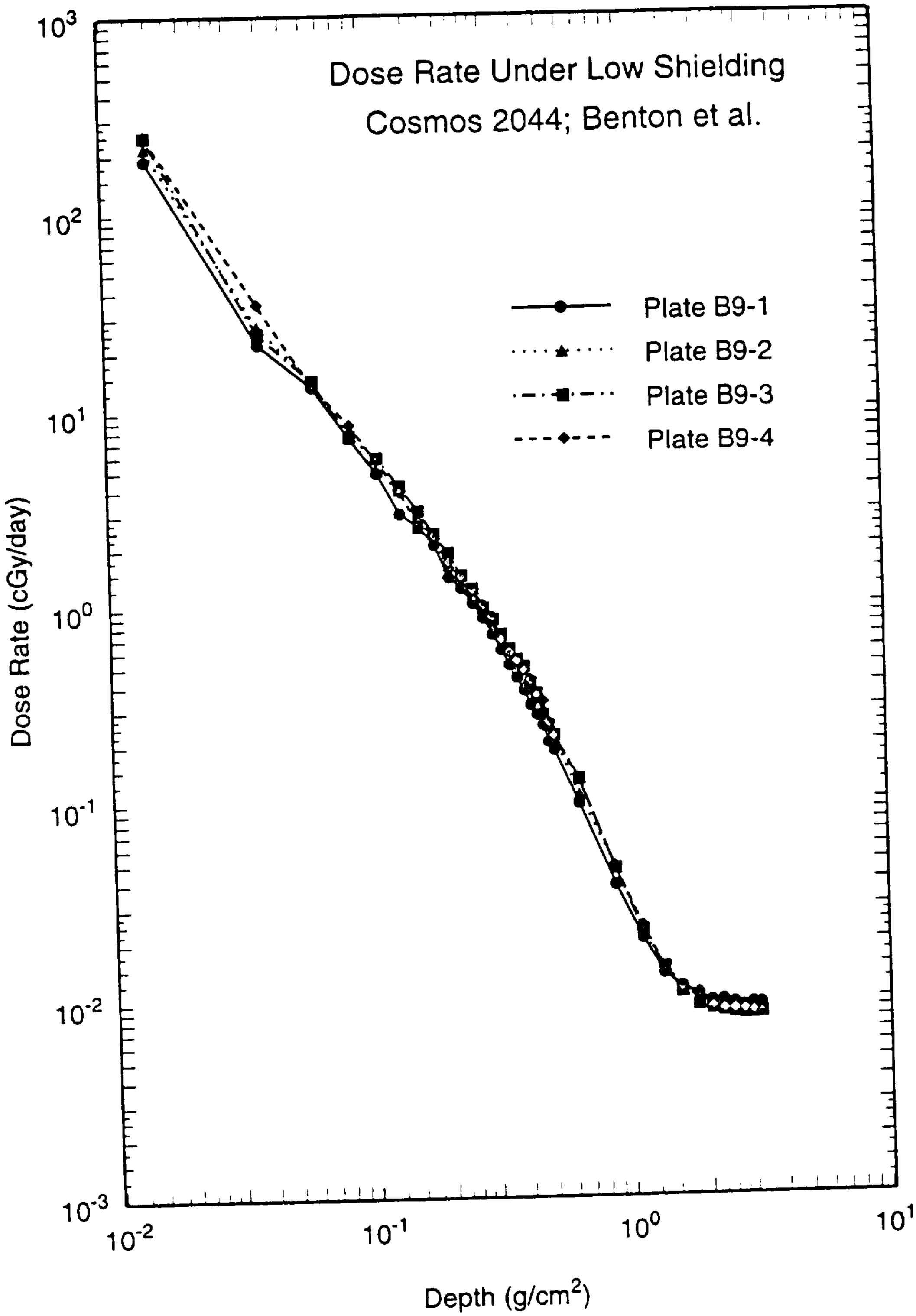


Figure 1-23. Dose rate as a function of shielding depth measured by USF in four containers on Cosmos 2044[11].

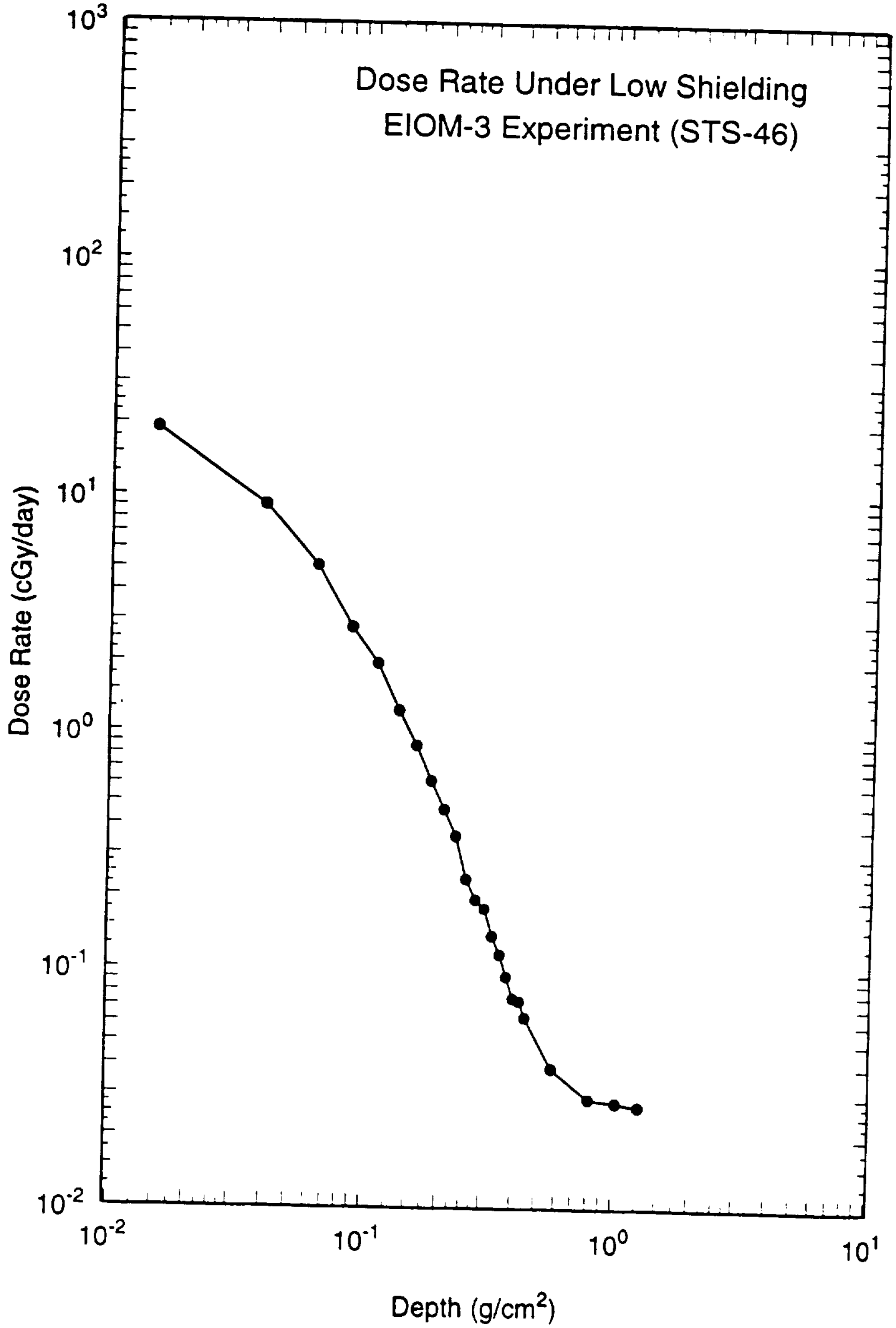


Figure 1-24. Dose rate as a function of shielding depth measured by USF in the open cargo bay of the Space Shuttle during STS-46[13].

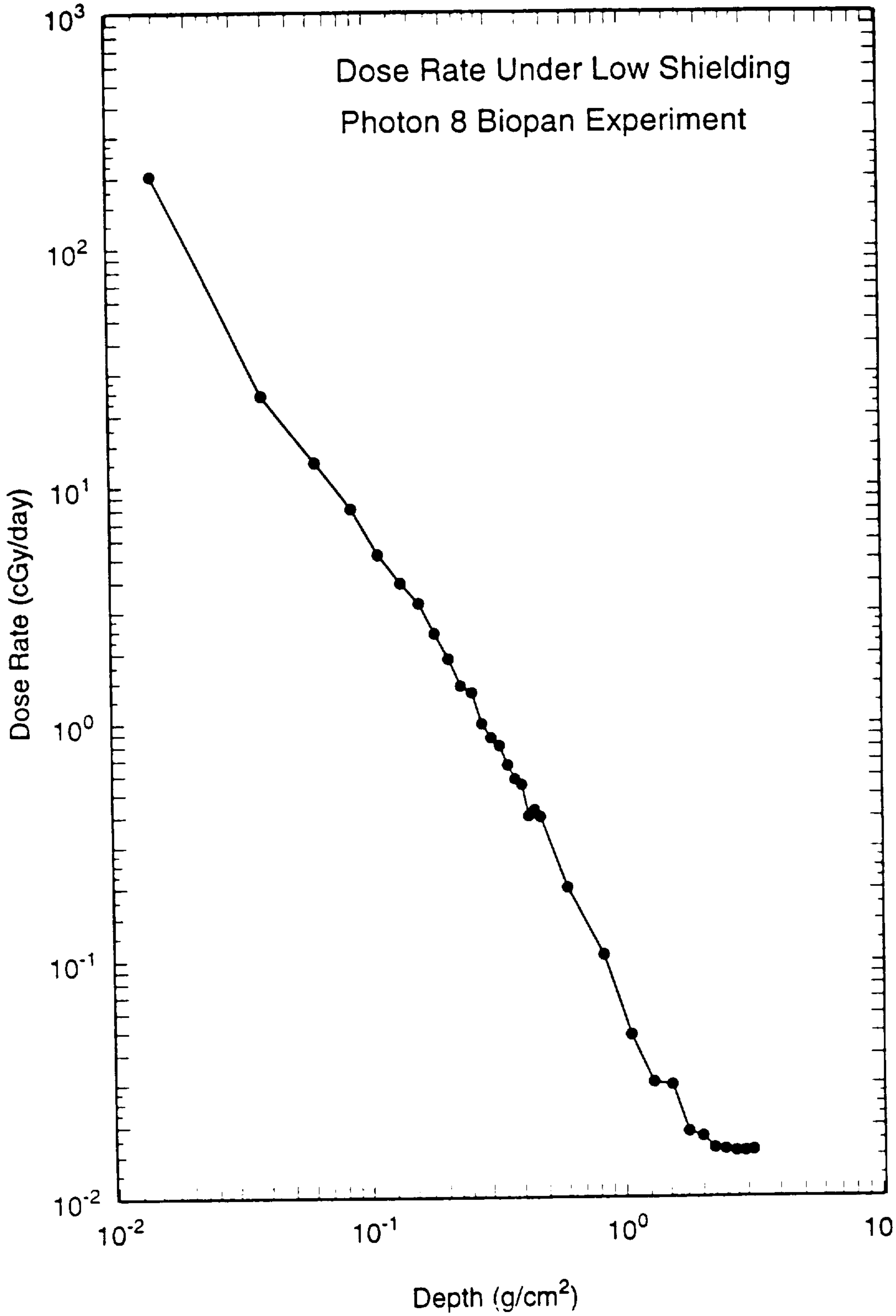


Figure 1-25. Dose rate as a function of shielding depth measured by USF on the Russian Photon 8 mission[14].

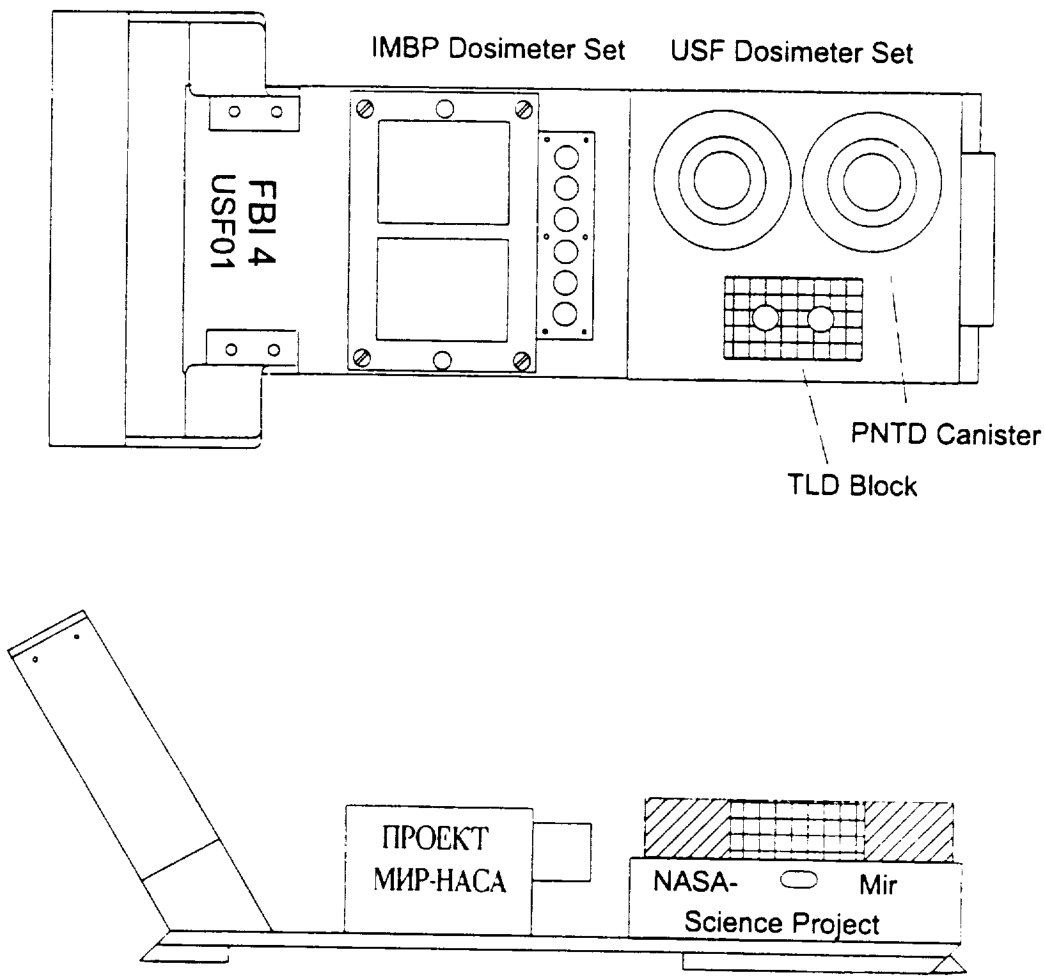


Figure 1-26. External Dosimeter Array (EDA) used during the NASA/Mir Science Program in 1997 to obtain measurements of dose rate as a function of shielding depth on the external surface of the Mir Space Station. TLD stacks were provided by USF and IBMP.

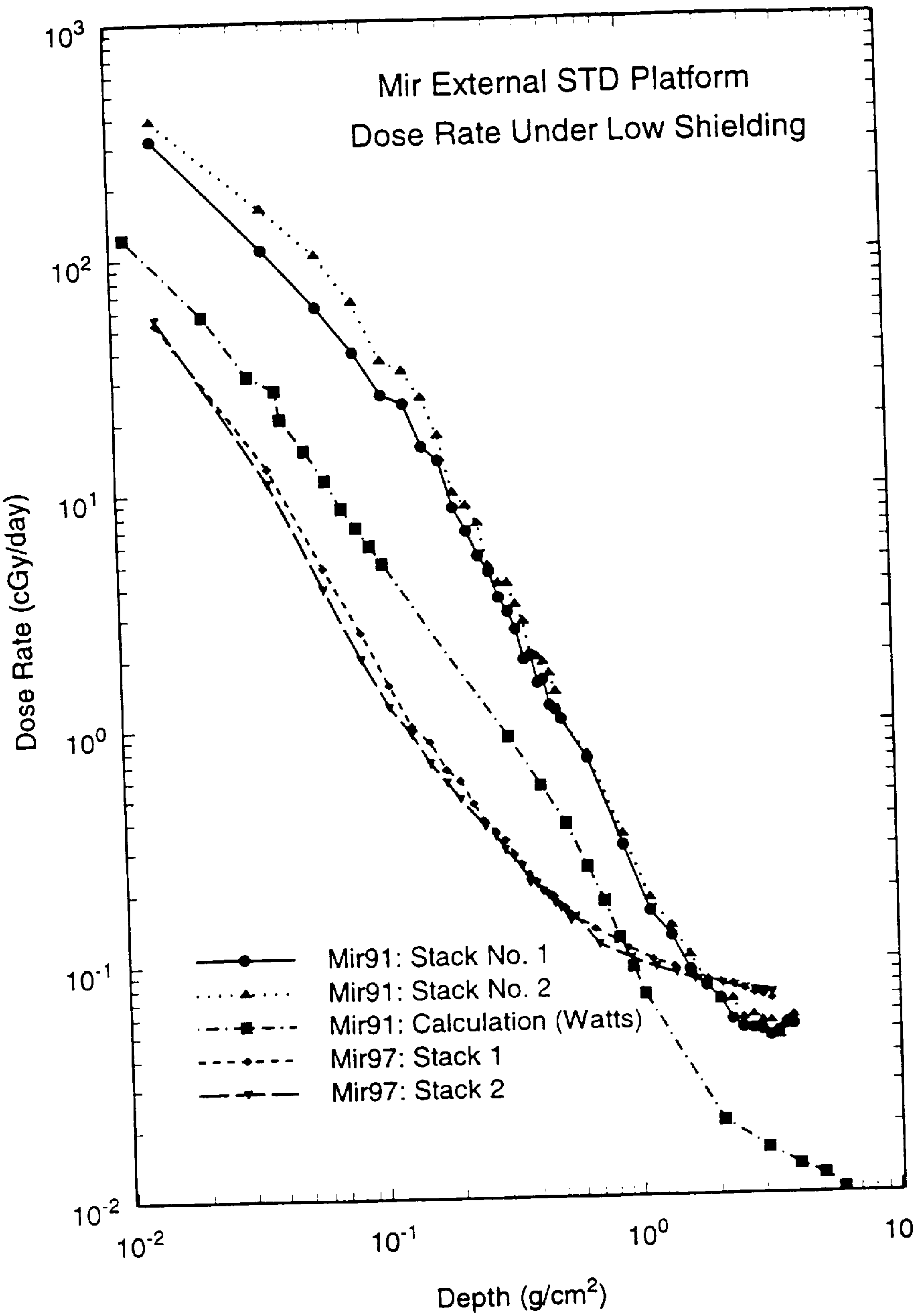


Figure 1-27. Dose rate as a function of shielding depth measured by USF on the outside of the Mir Station during June,1991 and for 130 days during 1997. Also shown is a model calculation of the June1991 exposure by Watts using AP8Max and AE8Max models[15,16].

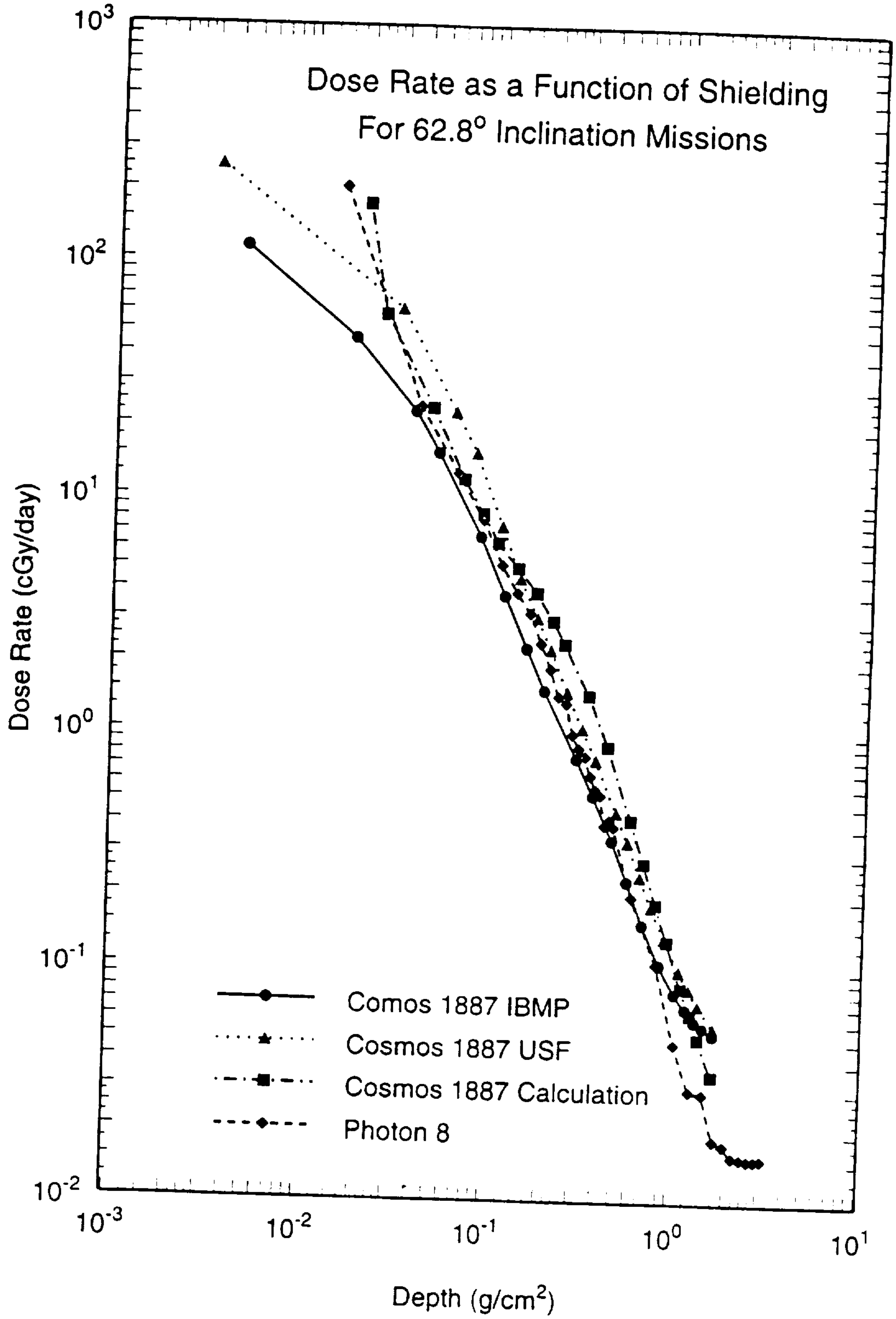


Figure 1-28. Comparison of four depth/dose measurements made aboard 62.8° inclination Cosmos missions[9,14].

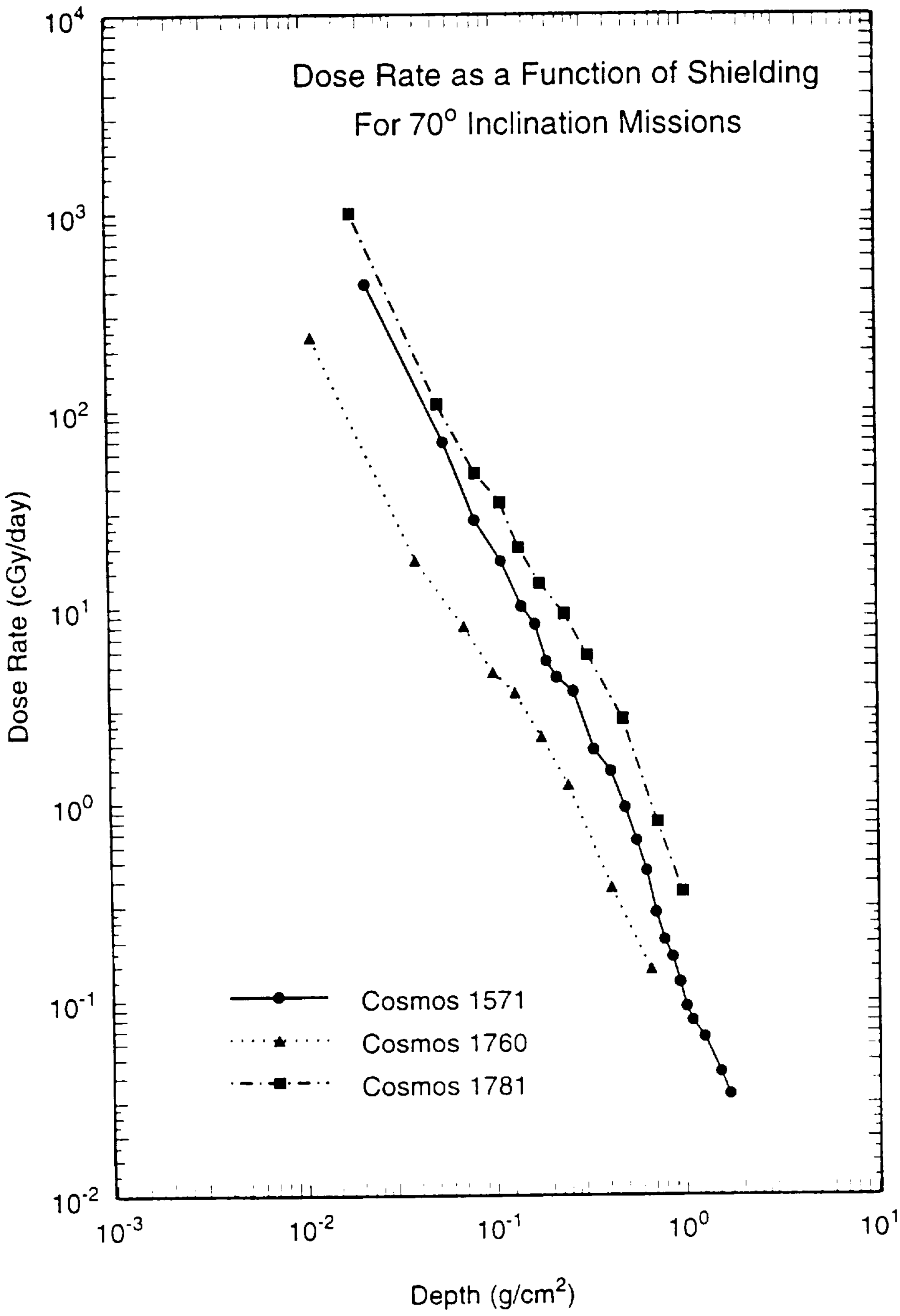


Figure 1-29. Comparison of four depth/dose measurements made aboard 70° inclination Cosmos missions[4].

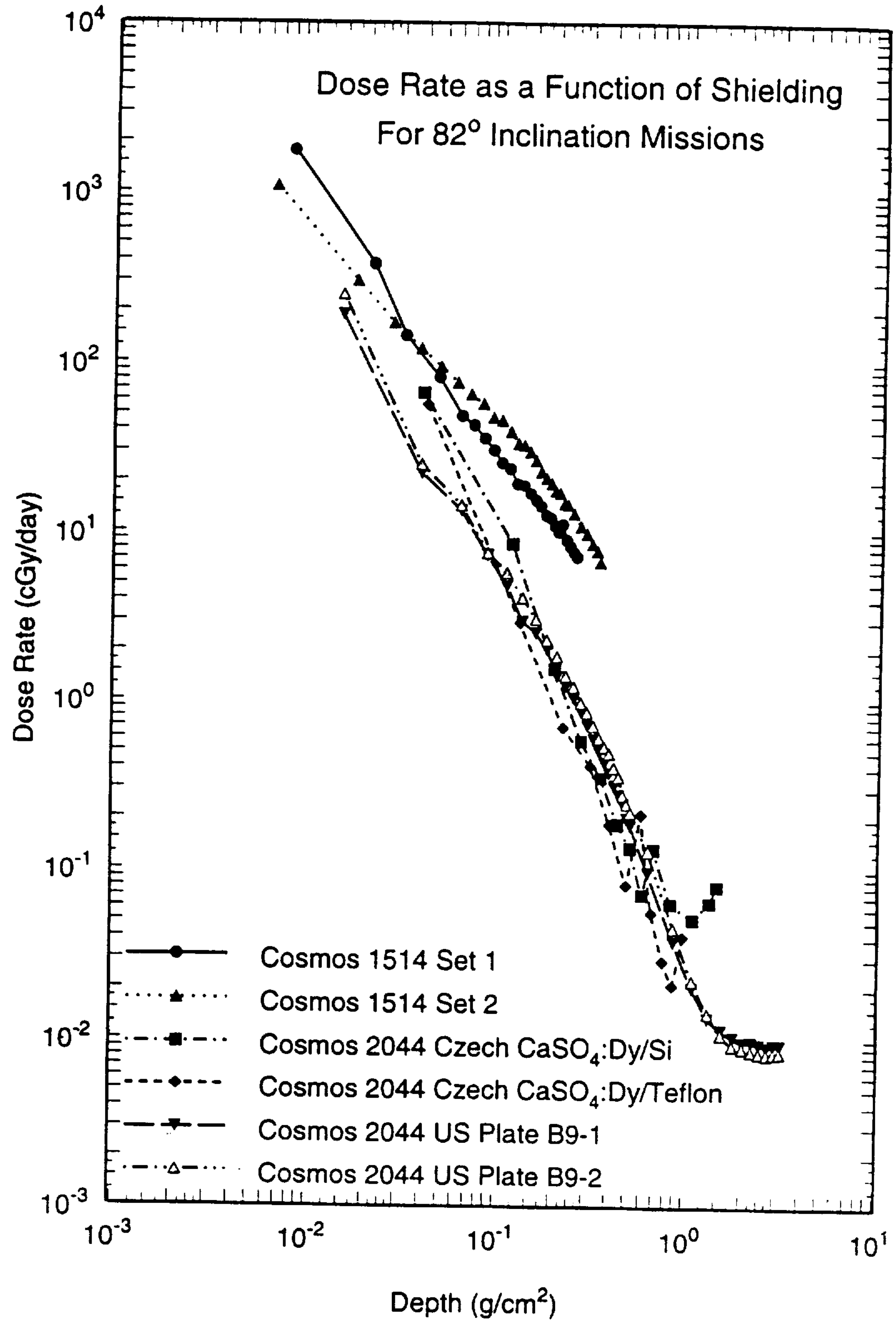


Figure 1-30. Comparison of four depth/dose measurements made aboard 82° inclination Cosmos missions[4,10,11].

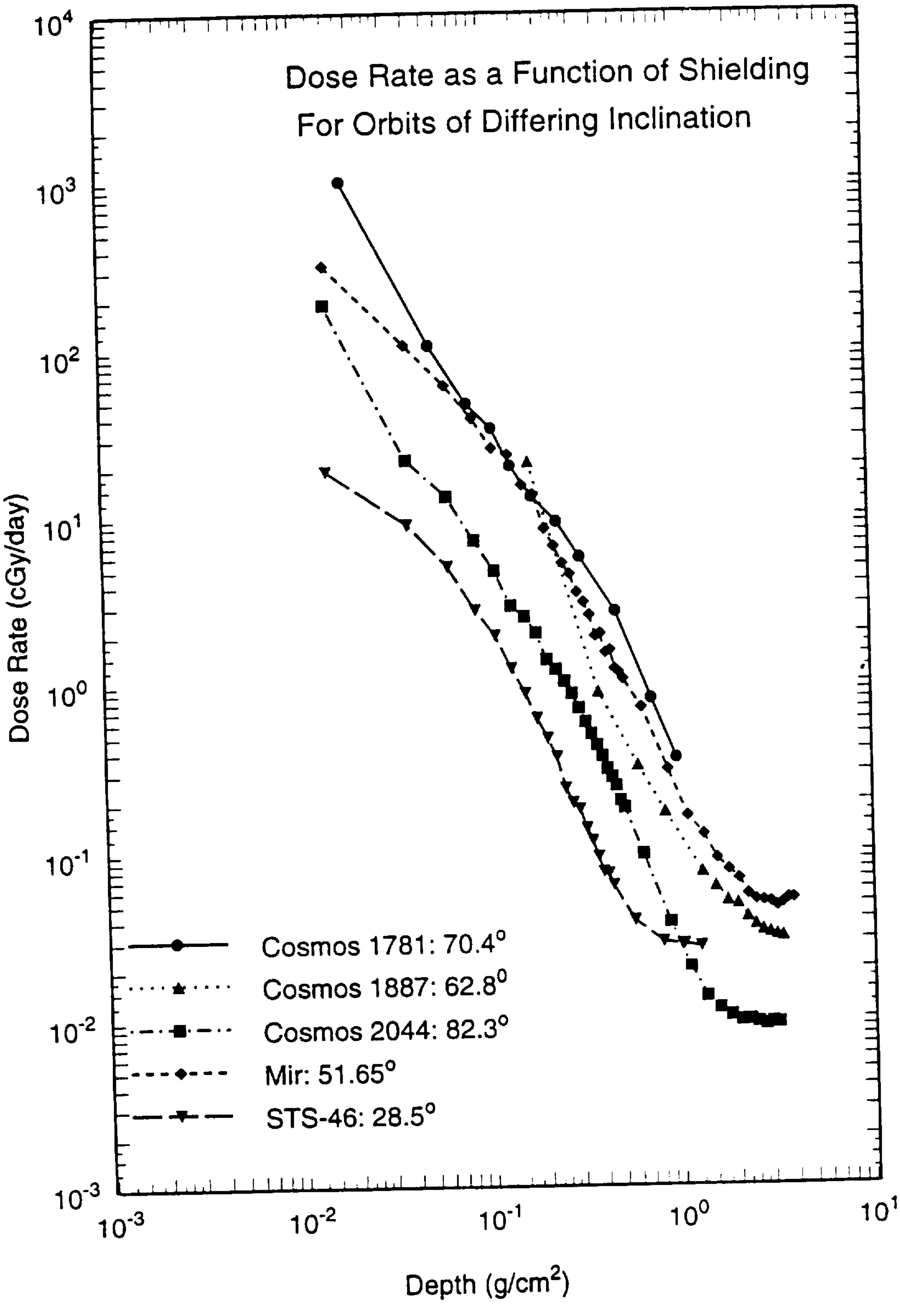


Figure 1-31. Comparison of four depth/dose measurements made at five orbital inclinations[4,11,13,15].

Chapter 2 – Measurements on Mir Station with Active Instruments

Despite the long life-time of the Mir orbital station (since June 1986) and the relatively large number of active radiation detectors deployed aboard Mir during this time, published environmental radiation data collected by these instruments remains relatively scarce. Only a small amount of data has been published to date and that data which has been made available is of limited value due to lack of detailed information concerning the instruments themselves and their shielding conditions. A list of active instruments for radiation measurement used aboard Mir since its activation is shown in Table 2-1. These include instruments developed and deployed by the Russians themselves, in collaboration with other countries and the instruments provided by NASA, ESA and other non-Russian agencies and deployed on Mir.

Table 2-1. Active Radiation Measurements Instruments used aboard Mir Station since launch.

Instrument	Investigators	Measured Quantities
R-16 Ion Chamber	Moscow State University	Dose, Dose Rate
Marya-2 spectrometer	Moscow Engineering Physics Institute	electrons 15-200 MeV protons 30-100 MeV
^{3}He counter	Moscow State University	neutrons < 10 MeV
Lyulin	Space Research Institute, Sofia, Bulgaria	Dose, Dose Rate,
Circe/Nausicaa TEPCs	French Atomic Energy Commissariat/CNES	LET Spectra, Dose, Dose Equivalent
DOSE A1	IBMP	Dose Rate
JSC TEPC	NASA-JSC	LET Spectra, Dose, Dose Equivalent
Radiation Environment Monitor (REM)	ESA	LET Spectra, Dose, Dose Equivalent
CREME	NASA/ESA	LET Spectra, Dose, Dose Equivalent
DOSTEL	University of Kiel/DLR	LET Spectra, Dose, Dose Equivalent
CHAPAT	DLR	limited LET information

The primary operational dosimeter aboard Mir is the R-16. It is an ion chamber similar in construction and sensitivity to ion chambers flown by MSFC aboard Skylab and early Spacelab missions. Only a limited amount of data from this instrument has been made available. The Marya-2 spectrometer is sensitive to electrons and protons and is similar to spectrometers flown aboard the Russian Salyut-6 and Salyut-7 orbital stations. There are a number of instruments aboard Mir for which no data is available. To date it appears that no data has been published for the ^{3}He neutron counter.

Collaborations between the Russians and investigators in various other countries have led to the development of a number of other instruments including the Lyulin by the Bulgarian Space Research Institute and the Circe and Nausicaa TEPCs by CNES and the French Atomic Energy Commissariat. Most recently the JSC TEPC has been permanently added to the complement of active radiation detectors aboard Mir. All of these instruments have been located near one another in the Core module (Base Block) of Mir, near the primary working space of the cosmonauts. Figure 2-1 shows the approximate location of the active dosimeters inside Mir. The shielding distribution for two of these instruments is shown in Figure 2-2[17].

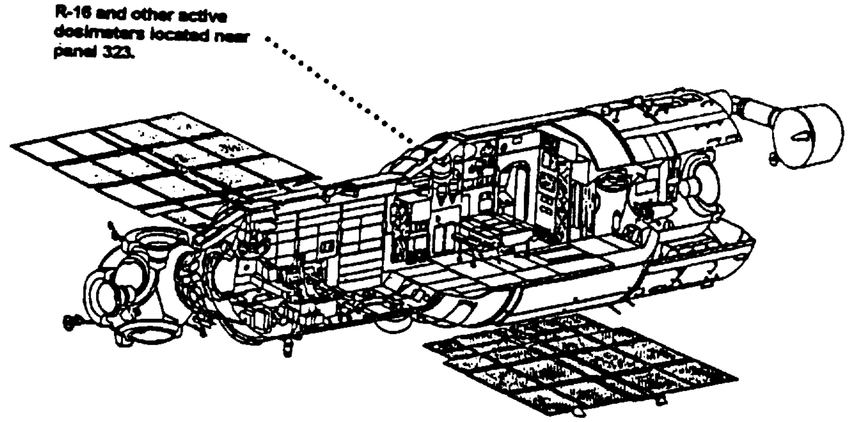


Figure 2-1. Location of R-16 and other active instruments in the Mir Core module.

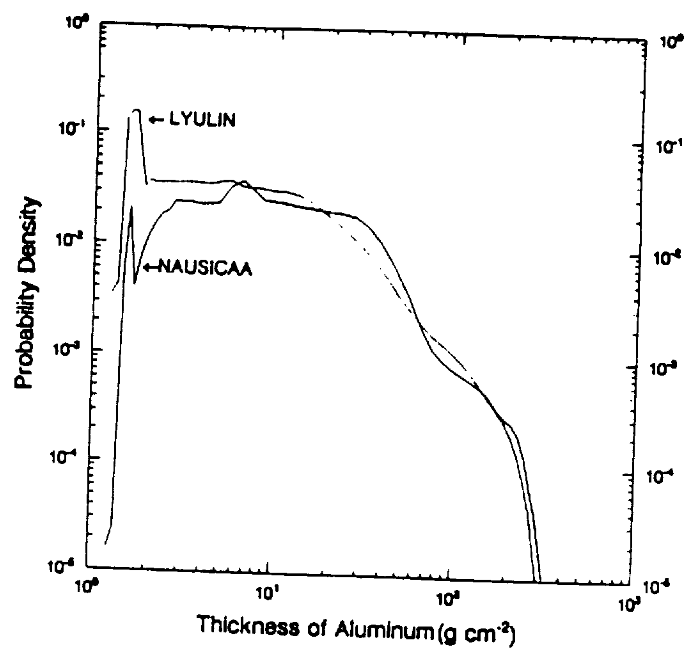


Figure 2-2. Shielding distributions for the Lyulin and Nausicaa instruments in the Core Module of Mir[17].

The remaining instruments in the list, REM, CREME, DOSTEL and CHAPAT have only been recently deployed aboard Mir and little or no data is yet available from them. The Pille TLD reader, while allowing for real-time read-out of doses from TLDs aboard Mir will be covered in the chapter concerning passive radiation measurements aboard Mir Station.

2.1 RESULTS FROM ACTIVE INSTRUMENTS

2.1.1 Russian R-16 Operational Dosimeter

The primary operational dosimeter onboard the Mir station is the R-16 radiometer. The R-16 consists of two IK-5G ionization chambers placed at right angles to each other and filled with argon gas to a pressure of 7 atm. The walls of the chamber are made of 0.5 g/cm^2 tissue equivalent material ($Z = 7.6$). The R-16 is similar in construction and performance to ion chambers flown by MSFC on Skylab and early Spacelab missions. R-16 can measure a dose rate ranging from 5×10^{-4} to 50 cGy/h with an error of ±20%. Total dose can range from 5×10^{-2} to 100 ± 20% cGy. Each pulse registered by the instrument is equivalent to a dose of 5×10^{-3} ± 10% cGy [18]. The R-16 is located in a ceiling compartment of the Core (Base Block) module of Mir station as shown in Figure 2-1.

Although the R-16 has been operational since the launch of Mir in June 1986, only a small amount of data from this instrument has been published to date. This data encompasses the solar particle events (SPE) of 1989-1992. Figure 2-3 is the absorbed dose measured by the R-16 and by a portable ion chamber IPD-2 during September-October 1989 showing the effect on dose of the series of SPEs that began on 29 September 1989. This data can be compared with data collected by Lyulin for the same time period. Figure 2-4 is the dose rate in mrad/day for the year starting 1 January 1991 and illustrating the major SPEs of March and June 1991. In Figure 2-5 dose rate as a function of altitude for the periods of 1 January to 31 May and 1 March to 31 March 1991 is plotted. Figure 2-6 shows dose rate from R-16 measured during 14 March to 25 June 1991 and 21 October to 12 November 1992 time periods, again encompassing several major SPEs[19].

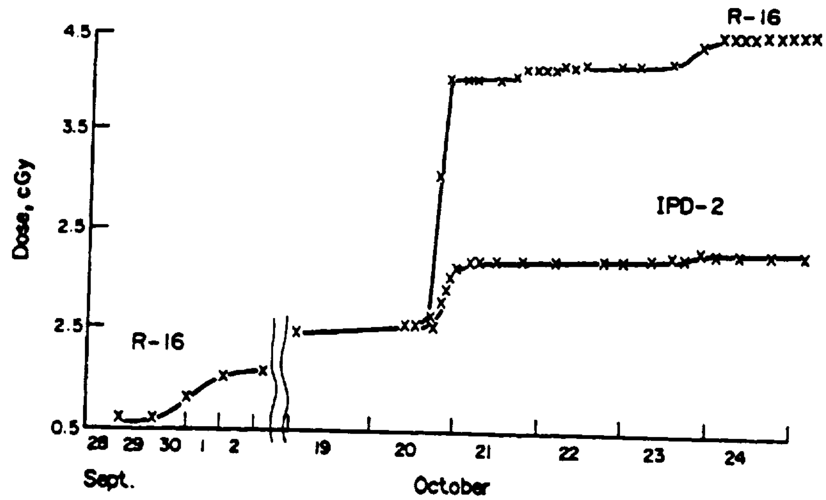


Figure 2-3. Absorbed dose as a function of time measured with R-16 and IPD-2 dosimeters in September-October 1989[18].

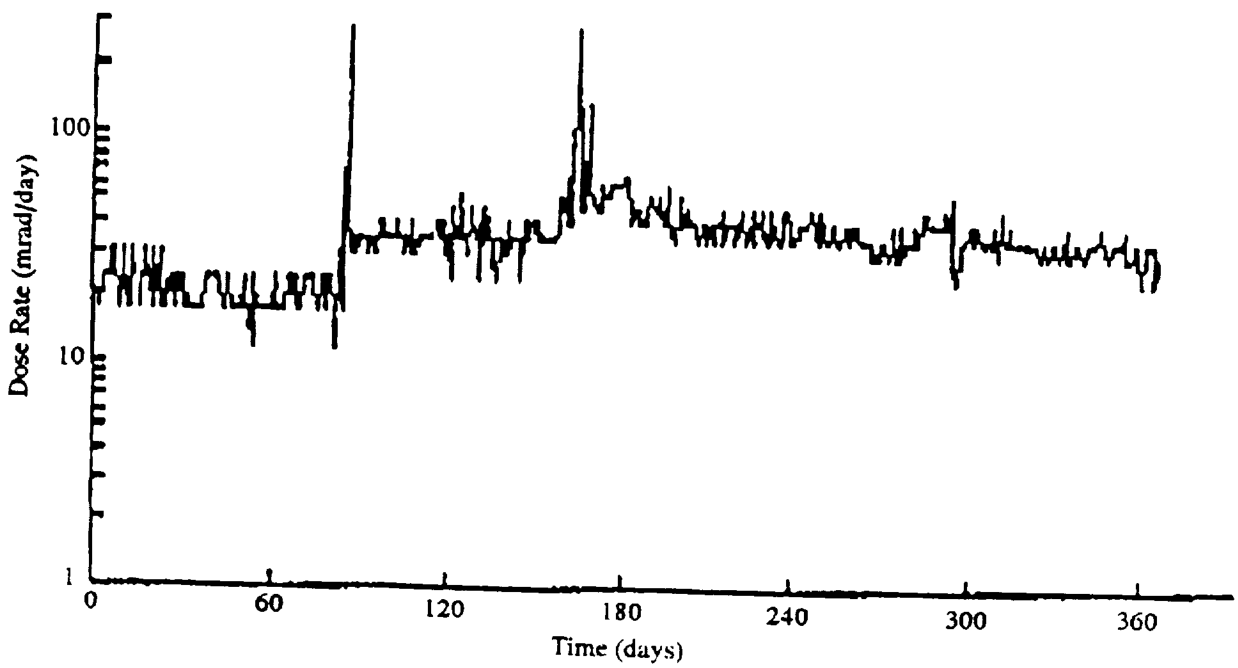


Figure 2-4. Dose rate (cGy/day) measured by R-16 operational dosimeter starting on 1 January 1991[19].

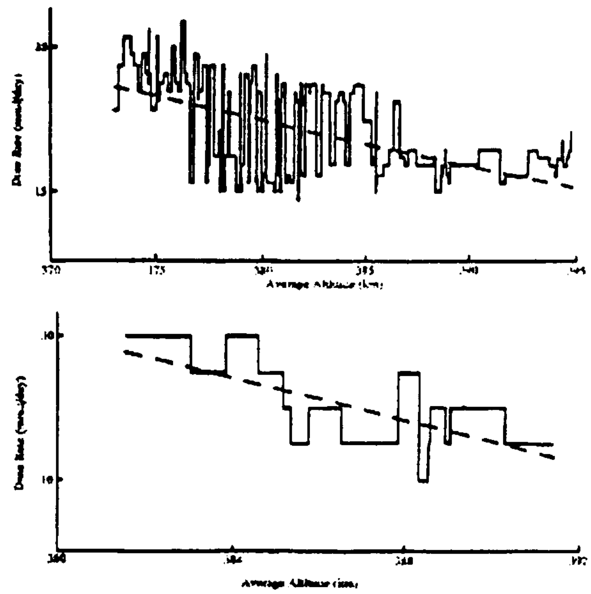


Figure 2-5. Absorbed dose rate as a function of average altitude of orbit for the period of 1 Jan. to 21 May 1991 (top) and 1 Mar. to 31 Mar. 1991 (bottom). The dashed line is a linear approximation[19].

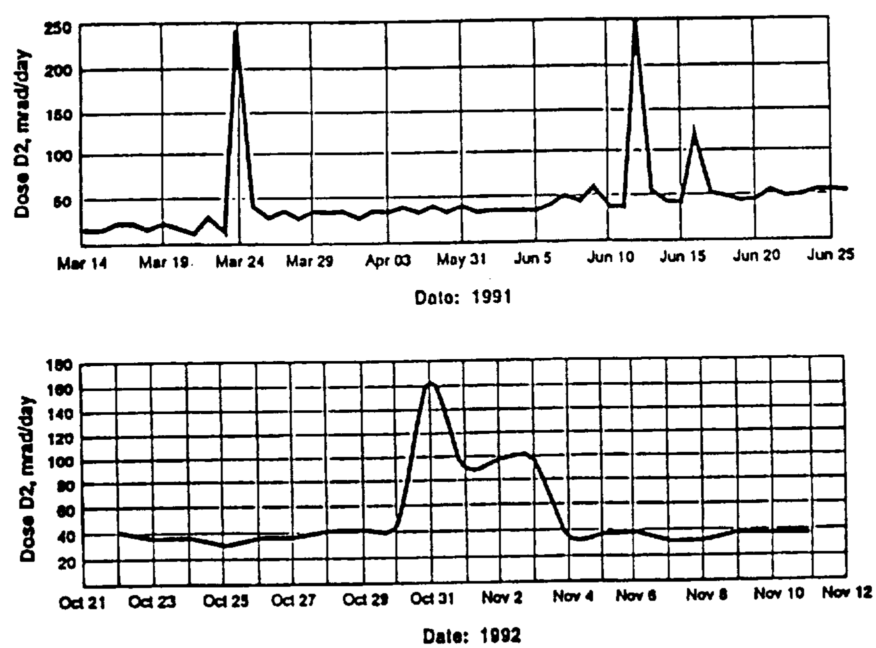


Figure 2-6. Total absorbed dose rate measured by R-16 as a function of time during the March to June 1991 time period (top) and the October to November 1992 time period (bottom)[19].

2.1.2 JSC Tissue Equivalent Proportional Counter

The JSC-TEPC is a tissue equivalent proportional counter developed at the NASA-Johnson Space Center and has been operating aboard Mir since September 1994. The instrument, pictured in Figure 2-7, consists of a right circular cylinder, 5.08 cm long and 5.08 cm in diameter, made of 1.9 mm thick tissue equivalent plastic and filled with low pressure propane gas. The detector simulates a 4 μm diameter cell. It is connected to a 256 channel A to D converter and is sensitive to ionizing particles of 0.2 to 1250 keV/μm. Resolution below 20 keV/μm is in 0.1 keV/μm steps and above 20 keV/μm is in 5 keV/μm steps. The full lineal energy spectrum is recorded every minute while the absorbed dose is computed every 2 or 20 s depending on dose rate[17].

Figure 2-8 shows dose rate since time of activation for the period of 3-6 September 1994. Total absorbed dose rate was 411.3 ± 3.31 μGy/day and is comparable to the dose rate measured for the same period by the R-16 operational dosimeter. The sinusoidal variation in dose rate is from galactic cosmic radiation while the sharp spikes represent passage of the Mir through the trapped protons of the SAA.

Figures 2-9 and 2-10 are the total (GCR + trapped) integral and differential LET spectra measured by TEPC during the 3-6 September 1994 period. Also shown are LET spectra measured by French Nausicaa for the same time period. The Nausicaa curves have been normalized to give the same total dose as TEPC. For all practical purposes, the LET spectra measured by TEPC and Nausicaa are identical, although the Nausicaa curves fall off more rapidly above 300 keV/μm[17].

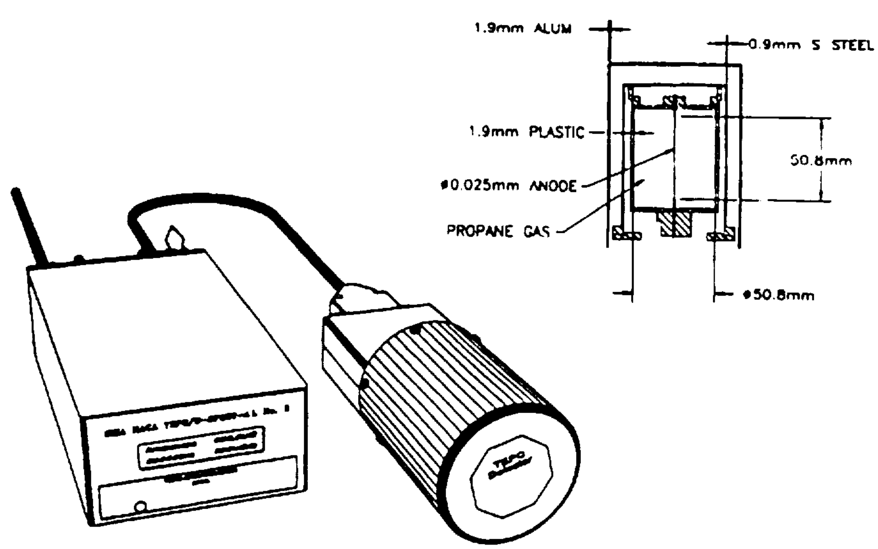


Figure 2-7. JSC-Tissue Equivalent Proportional Counter[17].

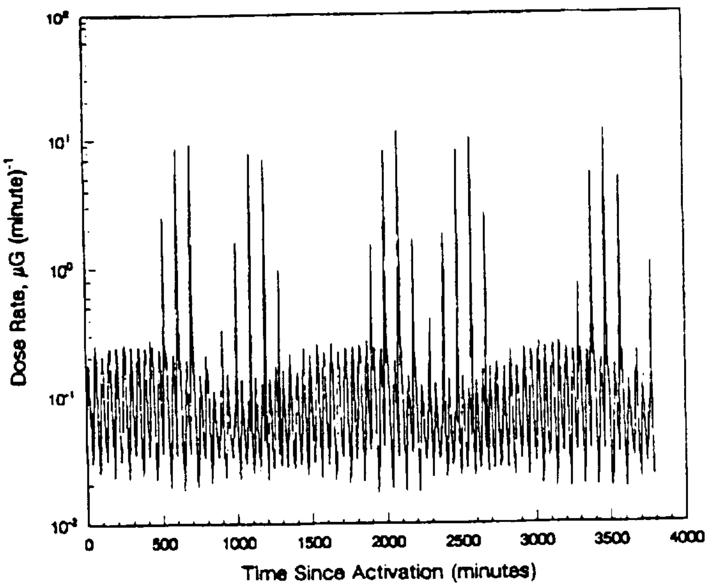


Figure 2-8. Dose rate measured by TEPC on Mir Orbital Station during the 3-6 September 1994 period[17].

Data collected while the spacecraft was passing through the SAA can be separated from data collected outside the SAA and in this way, the LET spectra from trapped particles can be separated from the LET spectra from galactic cosmic rays. Figures 2-11 and 2-12 are the integral and differential LET spectra measured by TEPC for trapped particles. Also shown are results from the AP-8 trapped proton model and BRYNTRN transport code for shielding distributions of the Nausicaa and Lyulin instruments. Figures 2-13 and 2-14 are the integral and differential LET spectra measured by TEPC for GCRs. Also included are calculated LET spectra for the Nausicaa and Lyulin shielding distributions using the Badhwar and O'Neil GCR model and the HZETRN transport code.

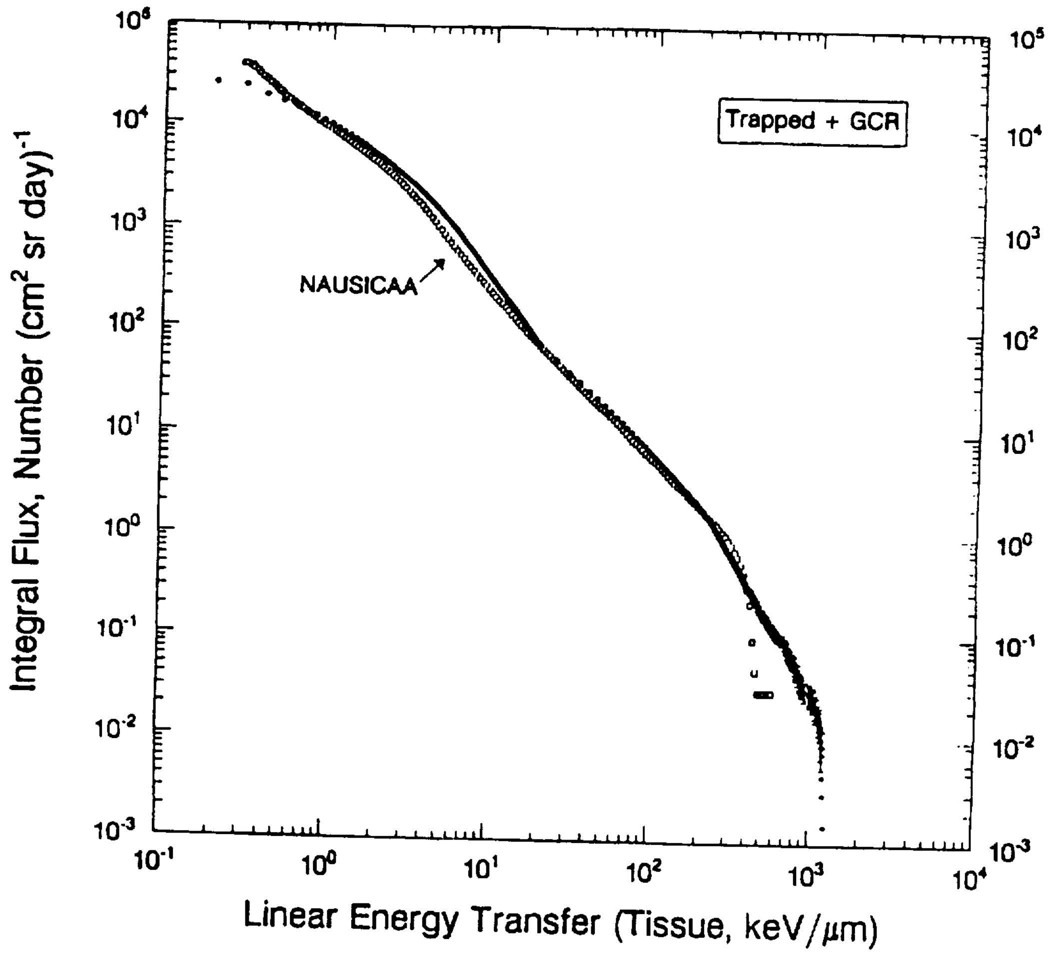


Figure 2-9. Total Integral LET Spectra measured by TEPC aboard Mir during 3-6 September 1994[17].

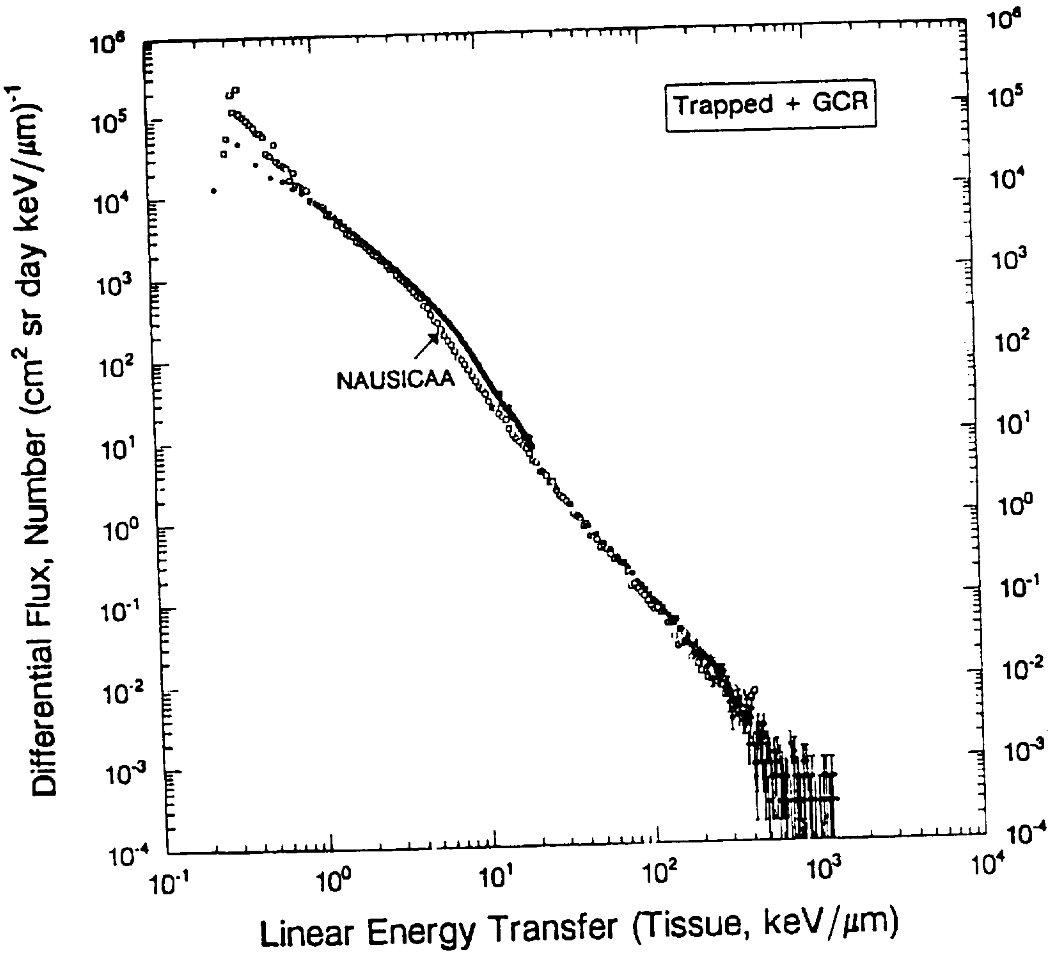


Figure 2-10. Total differential LET spectra measured by TEPC aboard Mir during 3-6 September 1994[17].

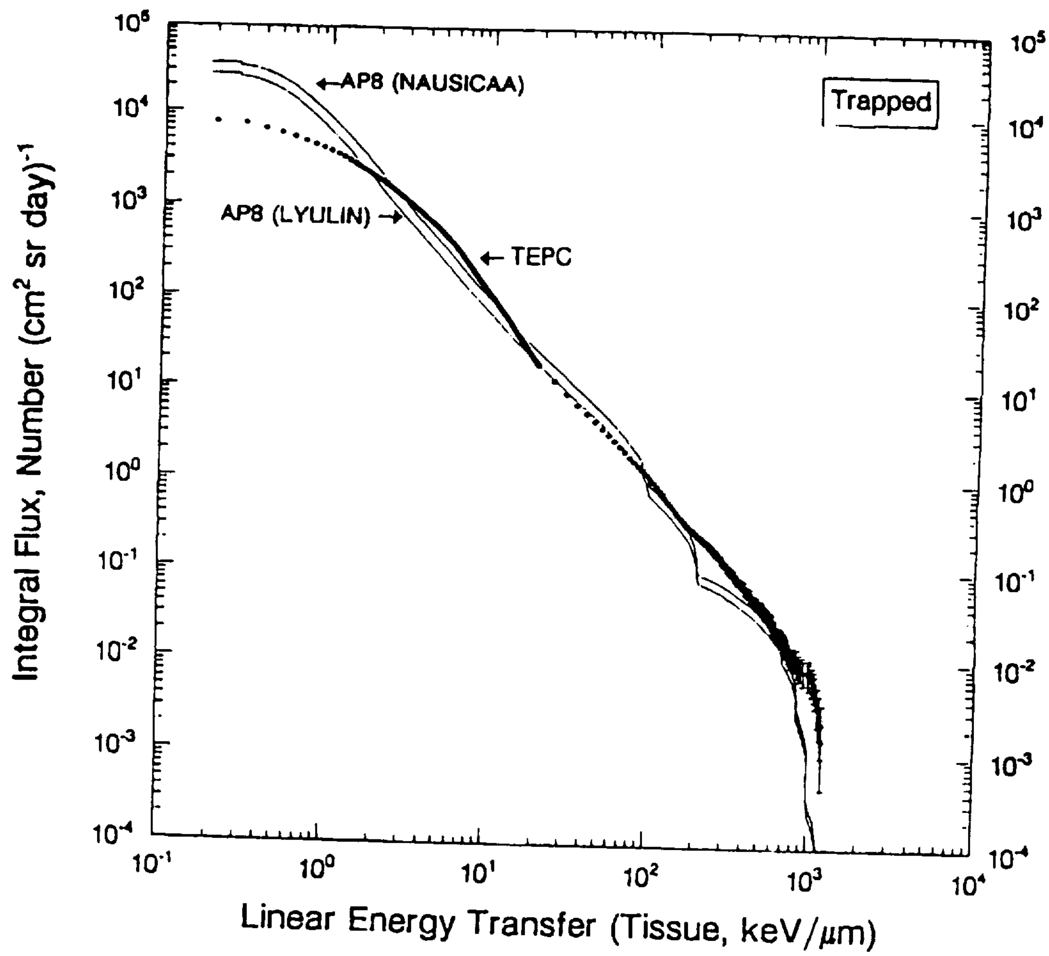


Figure 2-11. Trapped integral LET spectra measured by TEPC aboard Mir during 3-6 September 1994[17].

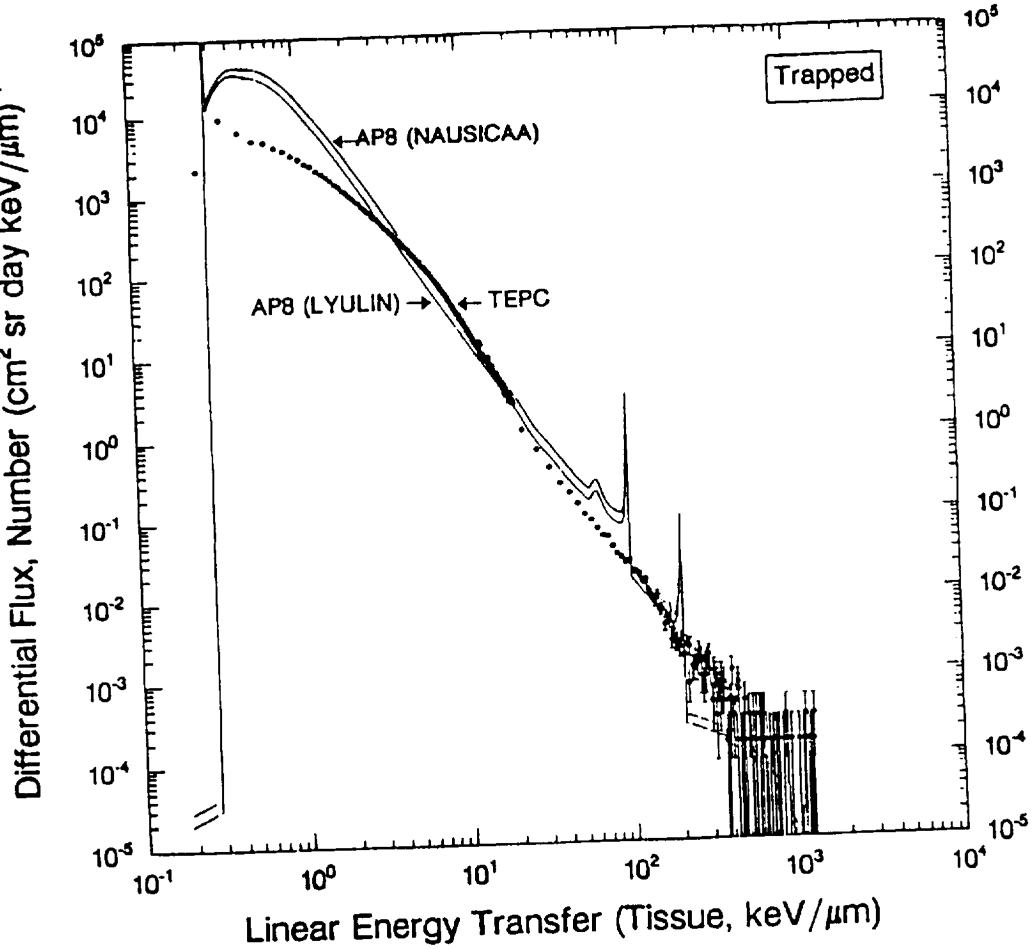


Figure 2-12. Trapped differential LET spectra measured by TEPC aboard Mir during 3-6 September 1994[17].

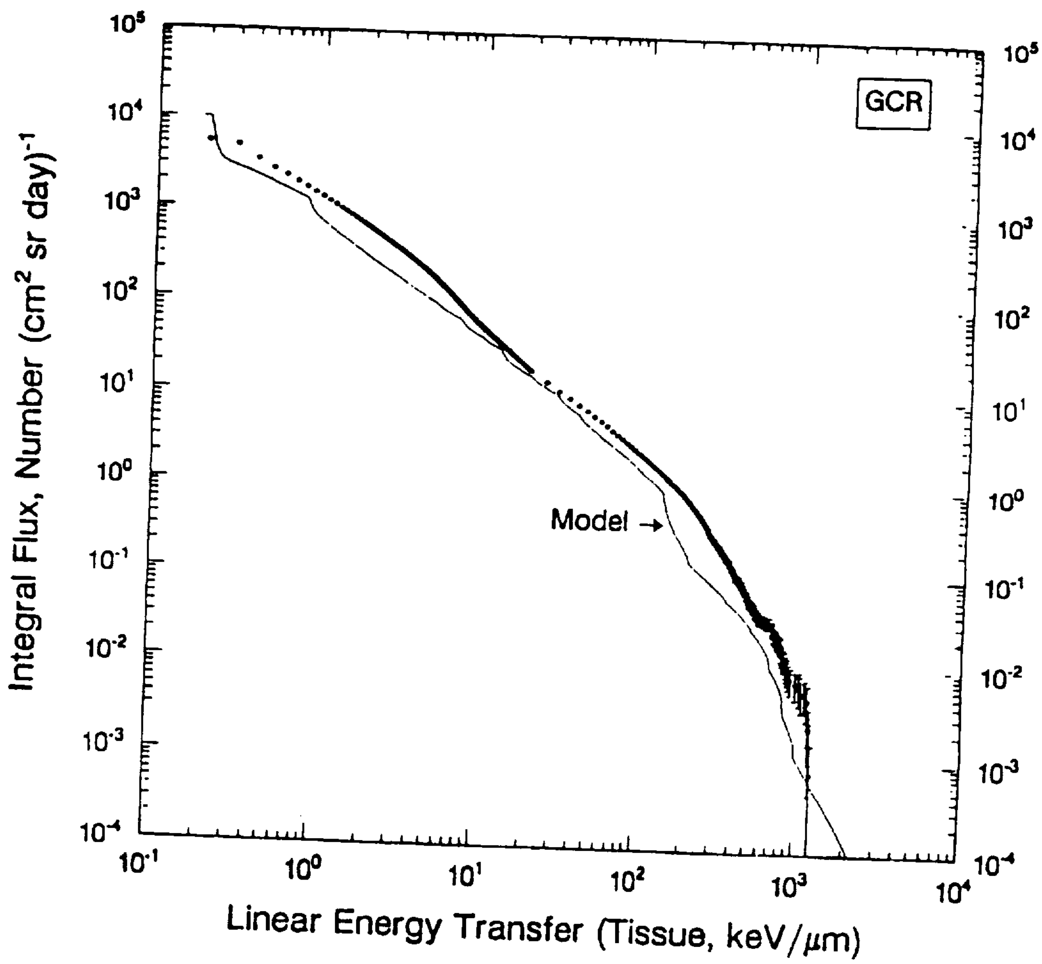


Figure 2-13. GCR integral LET spectra measured by TEPC aboard Mir during 3-6 September 1994[17].

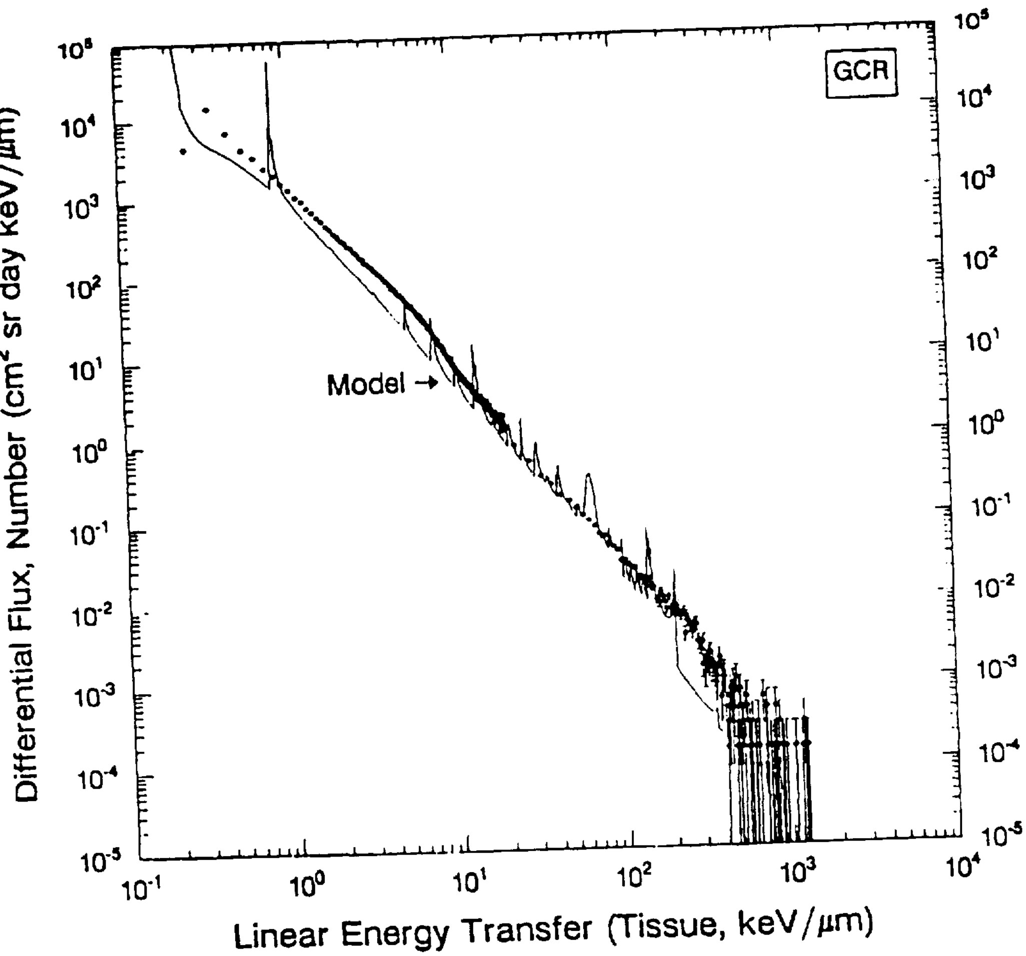


Figure 2-14. GCR differential LET spectra measured by TEPC aboard Mir during 3-6 September 1994[17].

2.1.3 Circe and Nausicaa

A collaboration between the French Atomic Energy Commissariat, CNES and the Institute of Biomedical Problems in Moscow resulted in the development of two tissue equivalent proportional counters that were flown aboard Mir–Circe and Nausicaa. Circe was operational between December 1988 and April 1989[20]. Nausicaa was deployed aboard Mir more recently. Both instruments are tissue equivalent proportional counters utilizing low pressure propane. Circe is sensitive to particles of LET between 3.5 and 1250 keV/μm while Nausicaa is sensitive to particles of LET between 0.2 and 1250 keV/μm.

Integral and differential LET flux spectra measured by Nausicaa in September 1994 are shown in Figures 2-9 and 2-10 along with LET spectra measured by the JSC-TEPC in the section on the JSC-TEPC[17]. Both graphs illustrate relatively close agreement between the two tissue equivalent proportional counters.

2.1.4 Lyulin

Lyulin is a portable, active dosimeter capable of measuring the flux and dose rate from ionizing radiation aboard spacecraft. It was developed by the Bulgarian Academy of Sciences in connection with the flight of the second Bulgarian cosmonaut in June 1988.[18,19] The active detector in the Lyulin instrument consists of a lithium-drifted silicon detector with an active area of 179.9 mm^2 and an active thickness of 599 μm. The instrument is portable and can be powered from four AA batteries. It is controlled by an 8-bit 65C02 microprocessor and has a 16 kbyte ROM, 48 kbytes RAM memory, a 16-key keyboard, 8 digit LED display a 16-byte parallel port for downloading data for telemetry and an RS-232 port for interface with a PC. Data from Lyulin is available for periods of major solar activity during the previous solar cycle, including the 1989-1991 events. Figure 2-15 shows dose rate as a function of L value for a number of days surrounding major solar particle events[21].

The Lyulin instrument is of limited usefulness since in can only detect particles with LET below 3 keV/μm. This means it cannot detect low energy protons, HZE particles or secondary particles with high LETs. It is also not able to discriminate between different particle types. Most of the particles detected by Lyulin are high energy protons in the SAA and polar electrons at the extreme latitudes of the Mir orbit.

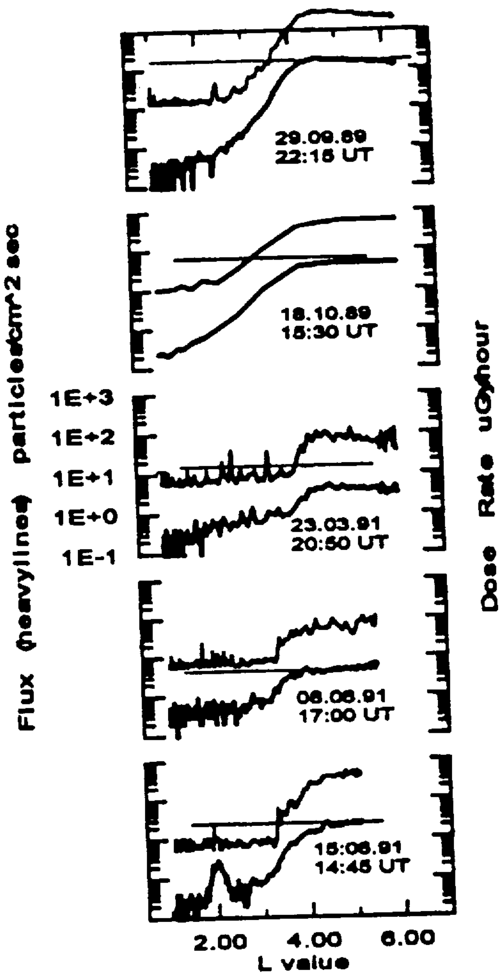
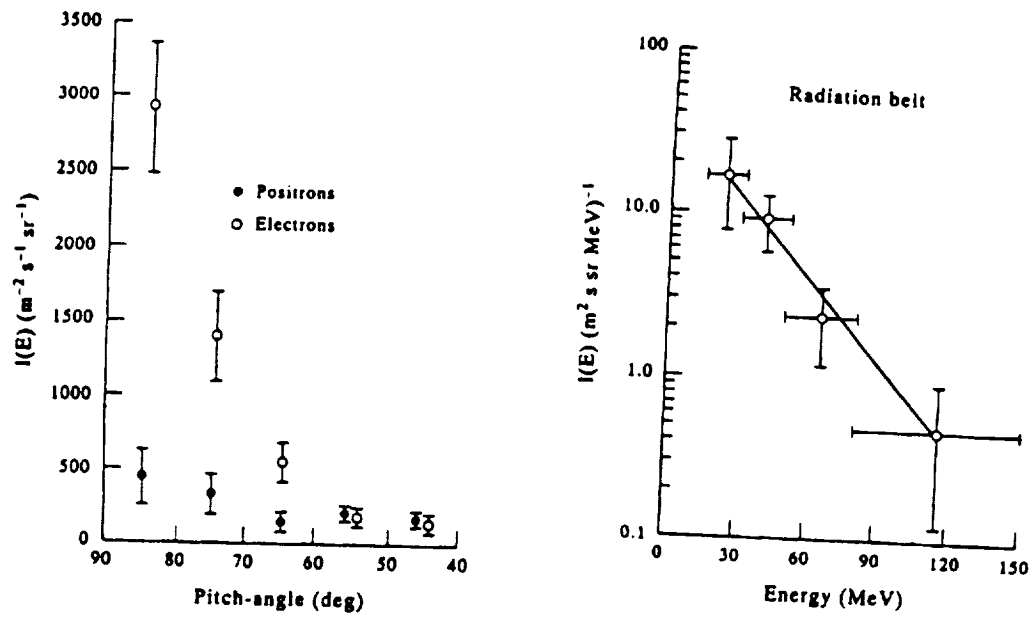


Figure 2-15: Dose rate measurements as a function of L from Lyulin made aboard the Mir Space Station between 1989 and 1991[21].

2.1.5 Marya-2 Electron Spectrometer

The Marya-2 instrument is a time of flight spectrometer capable of detecting electrons and positrons in the energy range of 15 to 200 MeV and protons of energy between 30 and 100 MeV.[22] Little information concerning the location, shielding or orientation of this instrument has been made available. However it is similar to other time of flight spectrometers deployed aboard earlier Soviet Salyut space stations. Figure 2-16 shows measurements made by Marya-2 in the SAA in the L range of 1.1 to 1.8.including the pitch angle distribution of electrons and positrons of 15-150 MeV and differential energy spectra from trapped electrons and excluding albedo electrons.



Figures 2-16. The pitch angle distribution of positrons and electrons and trapped electron energy spectrum measured by Marya-2 in the SAA[22].

2.1.6 ESA Radiation Environment Monitor

Radiation Environment Monitor (REM) was developed for ESA by the Paul Scherer Institute in Switzerland and will eventually be deployed aboard the International Space Station[23]. It consists of two silicon detectors capable of measured LET in 16 channels. Energy sensitivity of the channels ranges from 1 MeV cm^2/g to 2 GeV cm^2/g. The aperture of each detector consists of an aluminum cover with a ±45° conical opening. One of the detectors (e) is covered by a spherical dome of 0.7 mm Al. The second detector (p) is covered by 3 mm Al and 0.75 mm of Tantalum. These covers define the low energy thresholds for particles to penetrate the detector. The minimum electron energy is 0.7 MeV for the e-detector and 2.6 MeV for the p-detector. The minimum proton energy is 10 MeV for the e-detector and 34 MeV for the p-detector. The REM instrument is mounted externally to Mir with the detector apertures facing open space. Figure 2-17 shows dose rates measured by REM during 1995 in the SAA and at extreme latitudes. No LET spectra from REM has yet been published.

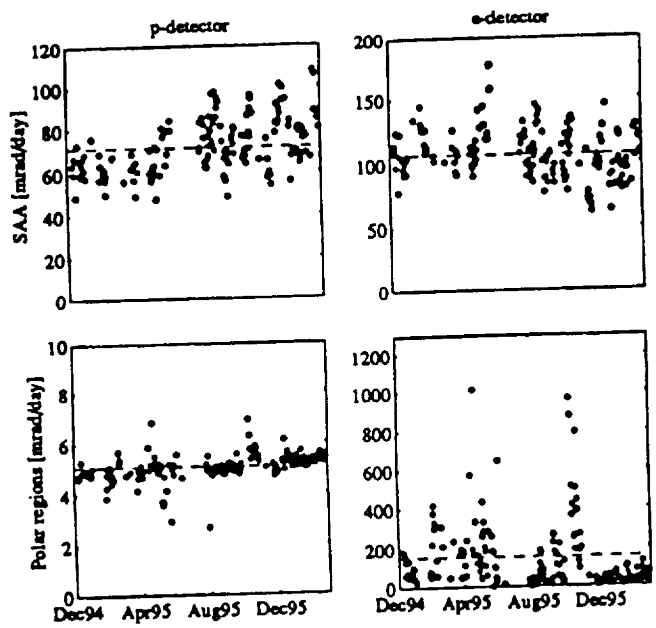


Figure 2-43. Dose rates measured by the p and e REM detectors on Mir in 1995 in the SAA and at extreme (polar) latitudes[23].

2.1.7 DOSTEL

DOSTEL is a charged particle telescope developed by the University of Kiel and DLR, Germany. It consists of two 6 cm^2, 315 μm Si detectors, and possesses an opening angle of 120° and a geometric factor of 6.58 cm^2 sr. DOSTEL is sensitive to charged particle of LET(Si) between 0.1 and 200 keV/μm, making it well suited for measurement of trapped protons in the SAA, but of limited value in measuring HZE particles. The instrument has flown on numerous Space Shuttle Missions as well as aboard the Mir during the Euromir 97 mission, and will be including within the Russian suite of radiation detectors to be flown aboard the ISS[24]

2.1.8 DOSE A1

The Dose A1 instrument, developed for the Institute of Biomedical Problems, Moscow, consists of 6 independent Si detectors and an interface unit. The 6 detectors can be distributed throughout the volume of the spacecraft and are connected to the interface unit via electrical cable. Each Si detector is capable of measuring charged particle flux in the range of 1 – 10^{-5} cm^{-2} s^{-1} and dose rate between 10^{-7} and 6×10^{-3} cGy/s. The LET threshold of the Si detectors was not available. The 6 Dose A1 detectors were located throughout the Core Module of Mir in early 1996 and data was regularly collected over a 10-23 day period and then transmitted to the ground. Due to technical problems with some of the detectors, not all 6 detectors were operational simultaneously. Table 2-2 presents dose rate measured inside and outside the SAA from three of the Si detectors. Since the instrument works in real time, measurements made inside the SAA are separable from those made outside and the assumption is made the all data collected inside the SAA are from trapped protons. Dose rate measured inside the SAA is comparable to that from GCR alone[25].

Table 2-2. Dose rate measured by three of the Dose A1 detectors inside the Core Module of the Mir Space Station in 1996[25].

Detector	Trapped Proton Dose Rate (μGy/d)	GCR Dose Rate (μGy/d)	Total Dose Rate (μGy/d)
4	112	66	278
6	137	133	270
7	97	101	198

2.2 DISCUSSION

Although a wealth of radiation data has been collected by Mir over the past decade much of it has yet to be used in validating environment models. To some extent this is due to the lack of shielding information for Mir and lack of specific information about the particular instruments. Limited shielding information is available for the Core Module (Base Block) of Mir where the R-16, Lyulin, Nausicaa and TEPC are or have been located and is discussed in Chapter 4 of this report.

The advent of the NASA/Mir Science Program and the ESA/Russian EuroMir missions have greatly increased international participation on the Mir. This has led to the full-time operation of the JSC-TEPC. TEPC data for the last three years will soon be available. Newer measurements such as that carried out by REM and CREAM may also prove useful in model validation.

Chapter 3 – **Recent LET Spectra Measurements on Mir**

A series of passive integrating measurements of environmental radiation using passive dosimeters located both inside and outside the Mir Space Station is being carried out by the University of San Francisco, in collaboration with Eril Research, Inc. (ERI), as part of the NASA-Mir Phase 1B Science Program. It is hoped that these measurements will significantly expand the U. S. data base at the 51.6° inclination orbit, provide detailed information on shielding effects, allow intercomparison of dosimetric methods and provide data for extensive testing of model calculations.

Measurements of linear energy transfer (LET) spectra are being carried out in the range of 5 to 1000 keV/μm using CR-39 plastic nuclear track detectors (PNTDs) in six area passive dosimeters (APDs) located throughout the interior of the Mir Station and at one location on the external surface of the Mir station. Total absorbed dose is being measured using thermoluminescent detectors (TLDs) included inside each APD. The combination of absorbed doses and LET spectra measured with the PNTDs will allow total dose, total dose equivalent and average Quality Factor (QF) to be determined for each APD location inside Mir. Comparisons will be made between LET spectra, dose and dose equivalent measured with different types of dosimeters including the APDs and other dosimeters currently in use on Mir.

In addition to the USF detectors, each APD contains a detector stack from Institute of Medical and Biomedical Problems (IMBP) in Moscow. Comparisons between these detectors will be for identical shielding geometry. APDs are also placed near the NASA-JSC TEPC microdosimeter and other Russian flight dosimeters. The agreement between dosimeter measurements by different countries and institutions is an important consideration in establishing a broad, reliable data base for the radiation environment in space. Comparisons will be made between three sets of measurements corresponding to the NASA-2/Mir-21, NASA-3/Mir-22 and NASA-4/Mir-23 missions to determine the change in radiation environment over time. The measurements will be made with identical APDs in the same locations on the Mir.

The use of TLDs to measure absorbed dose and CR-39 PNTDs to measure LET spectra has become standard on missions of the U. S. Space Shuttle. APDs similar to those deployed aboard Mir during the NASA/Mir Phase-1B Science Program have been included on several Space Shuttle missions since the inception of the program. These dosimeters have also been used aboard the Long Duration Exposure Facility, the ESA Eureca retrievable spacecraft, numerous Russian/Soviet Biocosmos missions and aboard Mir itself during the Mir-18 mission. Figures 3-1 and 3-2 show the locations of the four APDs in the Core module and the 2 APDs in the Kvant 2 module. In addition, Figure 3-2 shows the location of the External Dosimeter Array (EDA) mounted on the outside of the Kvant 2 module during the NASA-4/Mir-23 and NASA-5/Mir-24 missions. Results from absorbed dose measurements using TLDs are covered in Chapter 4 of this report.

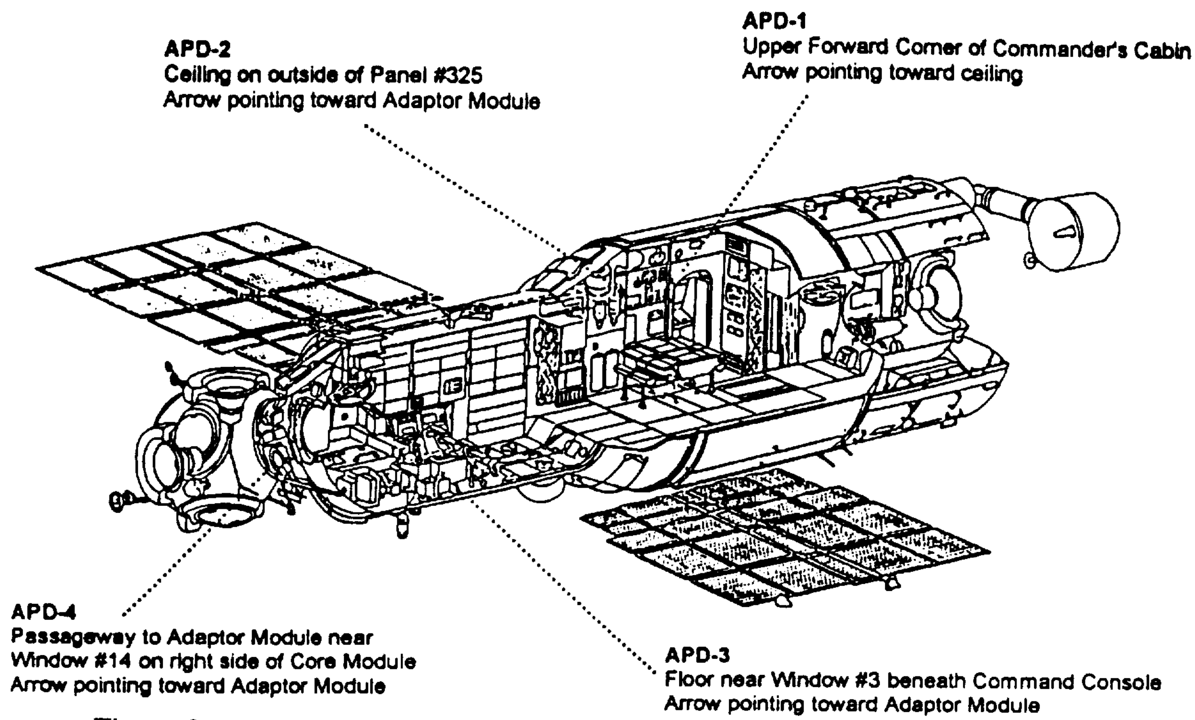


Figure 3-1. Locations of the four Area Passive Dosimeters (APDs) inside the Core Module of the Mir Orbital Station.

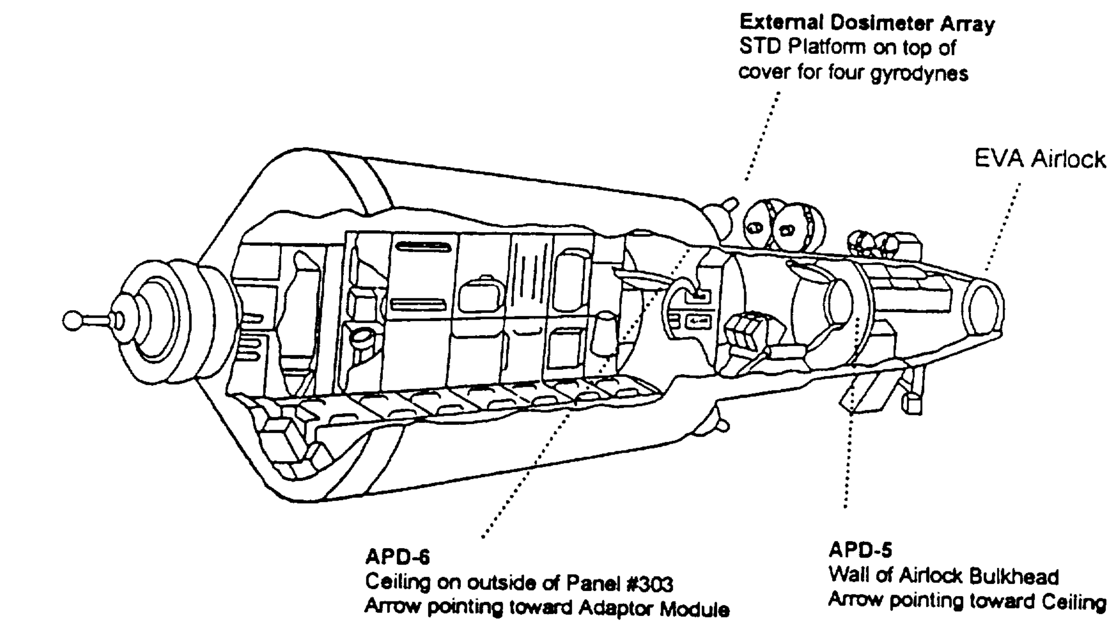


Figure 3-2. Locations of the two APDs inside the Kvant 2 module. Also shown is the location of the External Dosimeter Array (EDA) on the outer surface of the Kvant 2.

3.1 RESULTS OF NASA/MIR LET SPECTRA MEASUREMENTS

Integral LET flux, dose rate, and dose equivalent rate spectra have been generated from measurements of PNTDs. Figure 3-3 shows the integral LET flux spectra measured for each of the five APDs included in the NASA-2/Mir-21 missions. There is close agreement between the five curves throughout the entire measured range from 5 to 1000 keV/μm. The curve from APD-6 lies somewhat below the others for LET ≥ 100 keV/μm. This is consistent with the lower dose rate measured in APD-6. The high LET region is primarily made up of short-range (~8 μm) secondary particles produced in target fragmentation events when primary protons interact with the C and O nuclei of the detector. Greater shielding at the APD-6 location is seen in the decrease in total dose and in the relative number of target fragment events.

Most of the curves are seen to change slope between 250 and 350 keV/μm as indicated by the arrow in Figure 3-3. This knee occurs at the approximate maximum LET for α-particles. Below this knee, most of the LET spectra is believed to be made up of protons and α-particles produced in target fragmentation events. Above ~300 keV/μm, the spectrum is caused by GCR and by heavier target fragments. The lower rate of production of these heavier fragments relative to protons and α-particles is most likely responsible for the steeper slope above ~300 keV/μm.

Averaged dose rate spectra for each APD were generated from the averaged flux results and are shown in Figure 3-4. The PNTD dose rate results for LET ≥5 keV/μm are given in Table 3-1. Dose equivalent rate spectra were calculated using the ICRP-26 quality factors and the results are also presented in Figure 3-5. Table 3-2 gives the total dose equivalents determined from the combined TLD/PNTD measurements[26]. As seen in the LET flux spectrum, there is good agreement between all the dose rate and dose equivalent rate curves, though the spectrum measured for APD-6 falls somewhat below the others. As stated earlier, this is most likely due to the APD-6 location in the Kvant 2 module being more heavily shielded than the other four locations in the Core module.

Table 3-1. Dose and Dose Equivalent Rates from particles with LET ≥5 keV/μm measured in CR-39 PNTDs in the NASA-2/Mir-21 APDs[26].

APD No.	Dose Rate (LET ≥5 keV/μm) (μGy/d)	Dose Equivalent Rate (LET ≥5 keV/μm) (μSv/d)
1	26.3 ± 1.2	267 ± 18
2	29.7 ± 0.9	284 ± 12
3	31.9 ± 0.8	326 ± 11
4	38.0 ± 1.0	345 ± 14
6	31.4 ± 0.8	265 ± 9

Table 3-2. Total dose equivalent and dose equivalent rates for the five NASA-2/Mir-21 APDs[27].

APD No	Dose Equivalent (mSv)	Dose Equivalent Rate (μSv/d)
1	108.4 ± 0.4	576 ± 2
2	103.6 ± 0.3	551 ± 2
3	133.6 ± 0.3	710 ± 2
4	120.3 ± 0.3	639 ± 2
6	96.5 ± 0.2	513 ± 1

Figure 3-6 shows the integral LET flux spectra measured for APD-1 during the NASA-2/Mir-21 mission between 22 March and 26 September 1996 and during the NASA-3/Mir-22 mission between 16 September 1996 and 22 January 1997[26]. APD-1 was located at the entrance to the Flight Engineer's sleeping quarters in the large diameter portion of the Mir Core Module. The two spectra are in agreement within the limits of uncertainty of the measurement over the entire LET range measured, indicating that little change in the LET spectra above 5 keV/μm occurs over such short time scales.

3.2 COMPARISON OF USF PNTD AND JSC-TEPC LET SPECTRA

A comparison of the NASA-2/Mir-21 JSC-TEPC integral Lineal Energy Transfer flux spectrum with the PNTD results is shown in Figure 3-7[26,27]. The two spectra for both types of detector are comparable over almost the entire LET range shown. The deviation of the results below about 20 keV/μm is due to a fall off in the detection efficiency of the PNTDs. Differences above about 100 keV/μm are expected due to the differing chemical compositions of the two types of detector media. Above 100 keV/μm, most of the spectrum is produced by proton-induced, short-range, high-LET target fragments. Target fragment production is dependent on the elemental composition of the medium through with the primary protons pass. The greater concentration of C and O nuclei per unit volume in the CR-39 PNTDs versus the sensitive volume of the TEPC leads to the higher signal in the LET region above 100 keV/μm.

Figure 3-8 shows the Total, GCR and SAA Integral LET spectra measured by TEPC during the NASA-2/Mir-21 mission while it was located inside the Mir Core Module[27]. The total spectrum is dominated by GCR above ~10 keV/μm while below ~10 keV/μm the greatest contribution comes form the trapped protons in the SAA. This indicates that short-range high-LET target fragments produced by high-energy trapped protons do not make a significant contribution to the LET spectra as measured by TEPC. This differs from results seen in PNTDs where short-range target fragments appear to dominate the high-LET portion of the spectrum. A study to discriminate GCR particle tracks from target fragment tracks in PNTDs exposed aboard Mir is currently being undertaken in an attempt to verify this apparent difference.

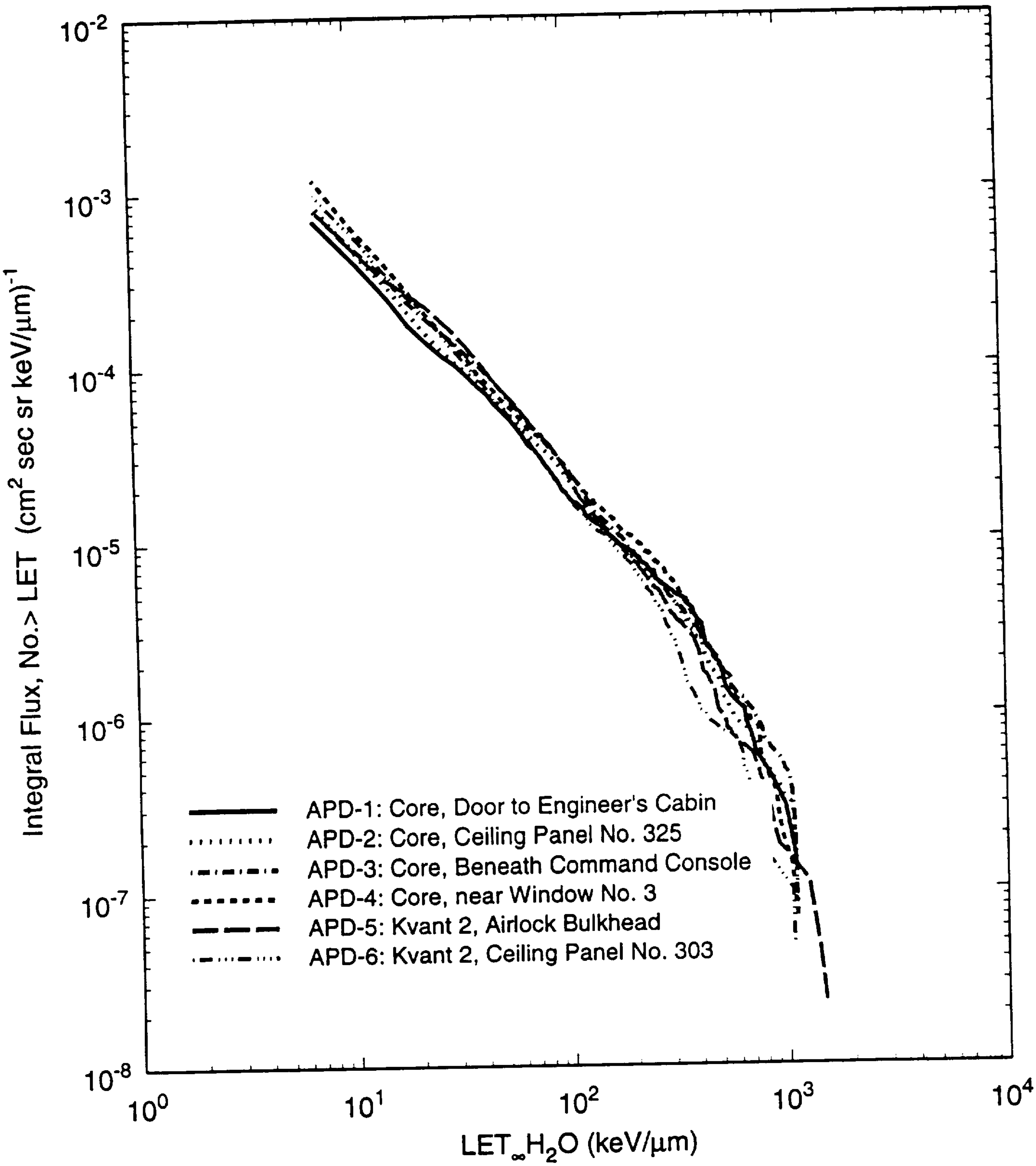


Figure 3-3. Integral LET flux spectra measured inside the Mir Orbital Station during the NASA-2/Mir-21 mission by the USF/ERI Environmental Radiation Measurements Experiment. 22 March – 26 September 1996[26].

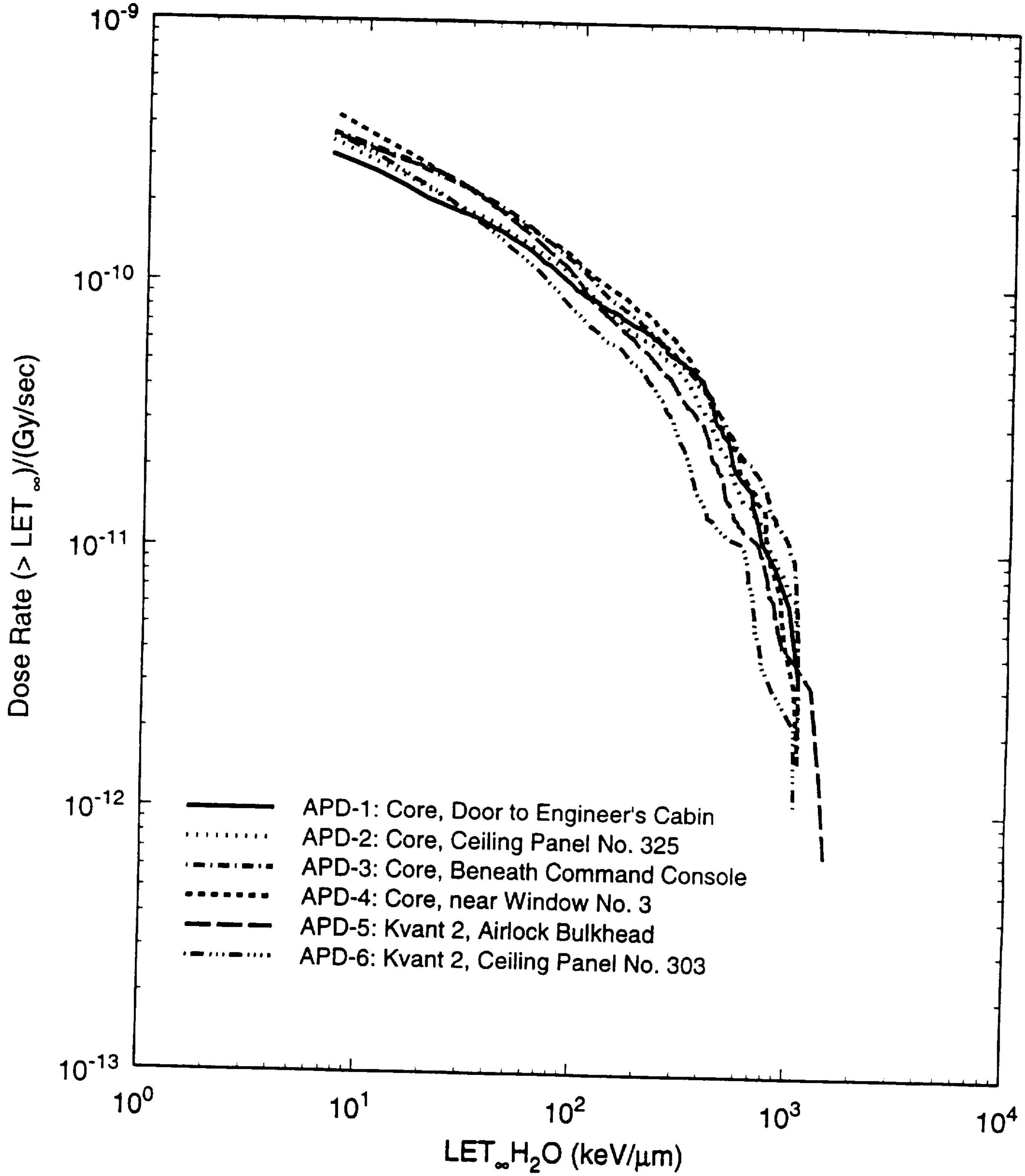


Figure 3-4. Integral LET dose rate spectra measured inside the Mir Orbital Station during the NASA-2/Mir-21 mission by the USF/ERI Environmental Radiation Measurements Experiment. 22 March – 26 September 1996[26].

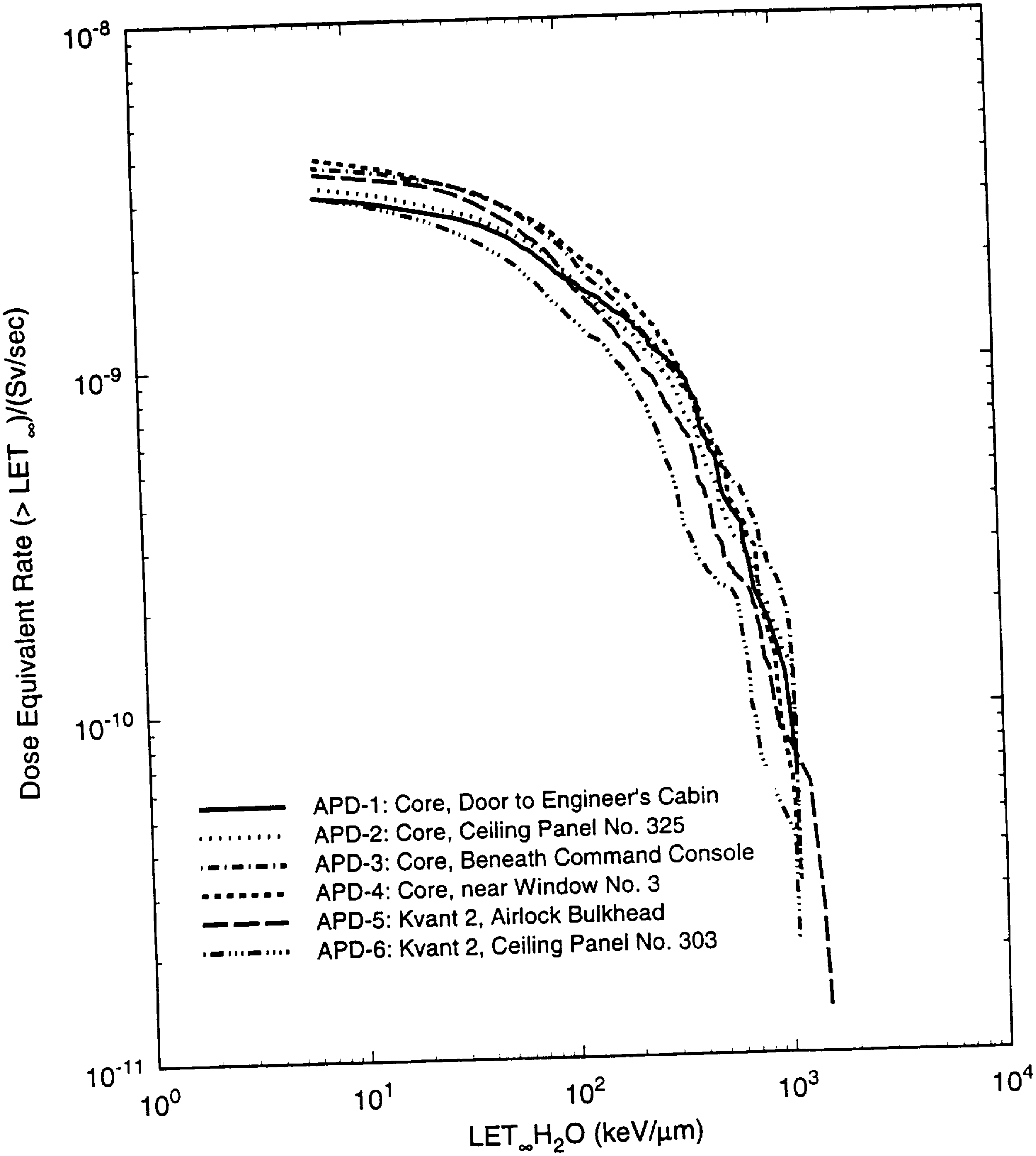


Figure 3-5. Integral LET dose equivalent rate spectra measured inside the Mir Orbital Station during the NASA-2/Mir-21 mission by the USF/ERI Environmental Radiation Measurements Experiment. 22 March – 26 September 1996[26].

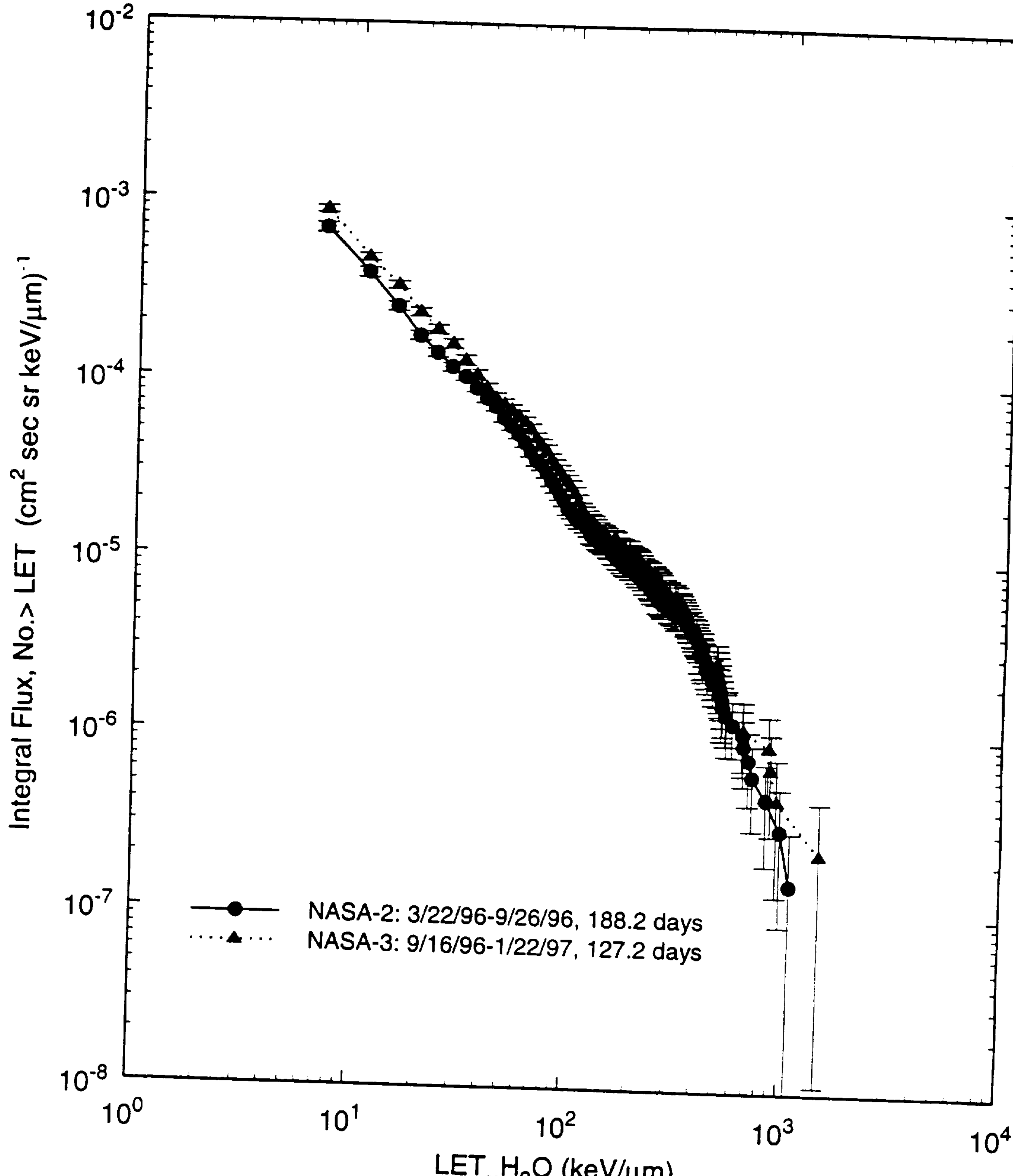


Figure 3-6. Integral LET flux spectra measured inside the Mir Orbital Station at the APD-1 location during the NASA-2/Mir-21 (22 March–26 September 1996) and NASA-3/Mir-22 (16 September, 1998-22 January 1997) missions by the USF/ERI Environmental Radiation Measurements Experiment[26].

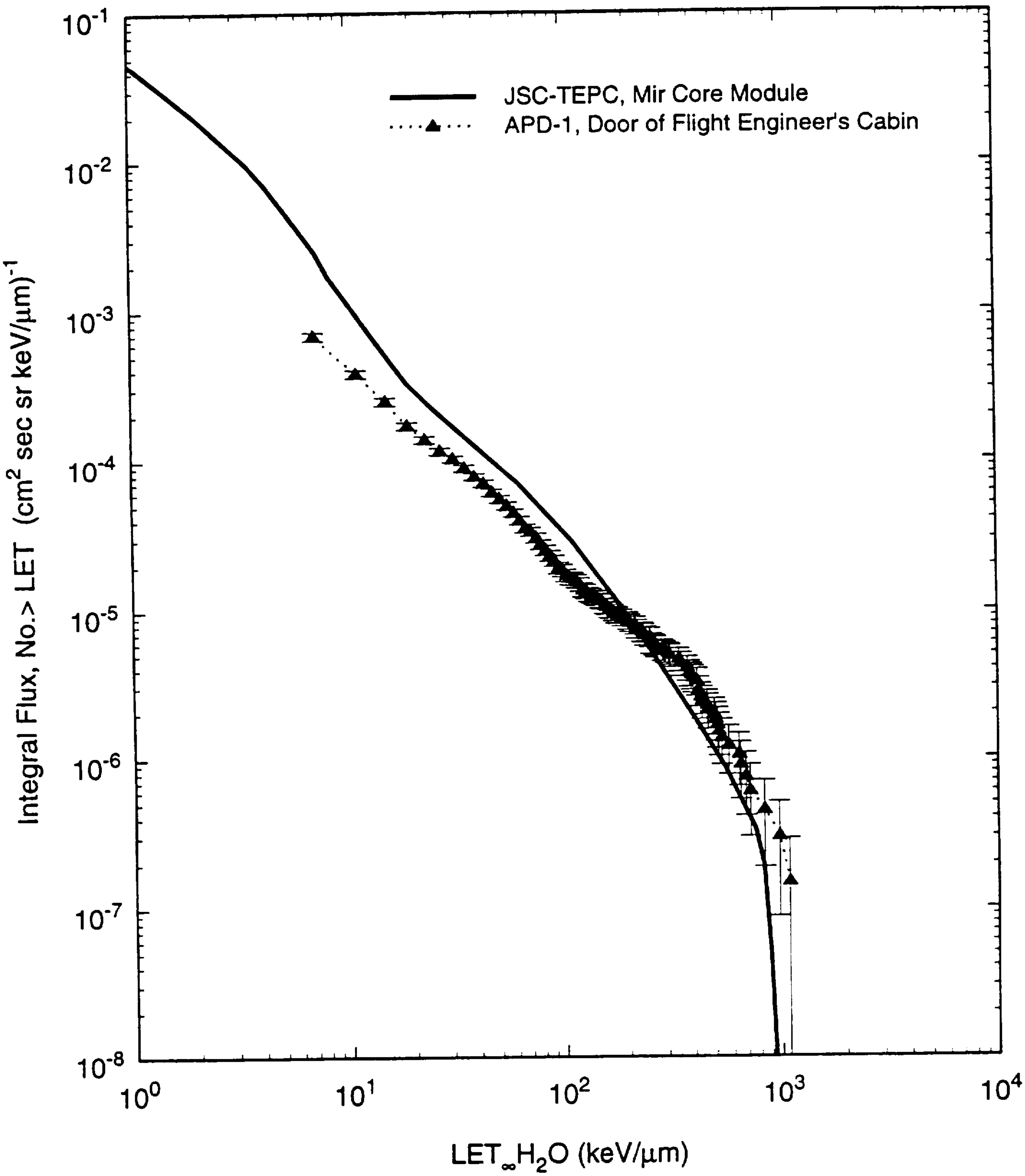


Figure 3-7. Comparison of Integral LET flux spectra measured inside the Mir Orbital Station during the NASA-2/Mir-21 mission by the USF/ERI Environmental Radiation Measurements Experiment and the NASA-JSC Tissue Equivalent Proportional Counter[26,27].

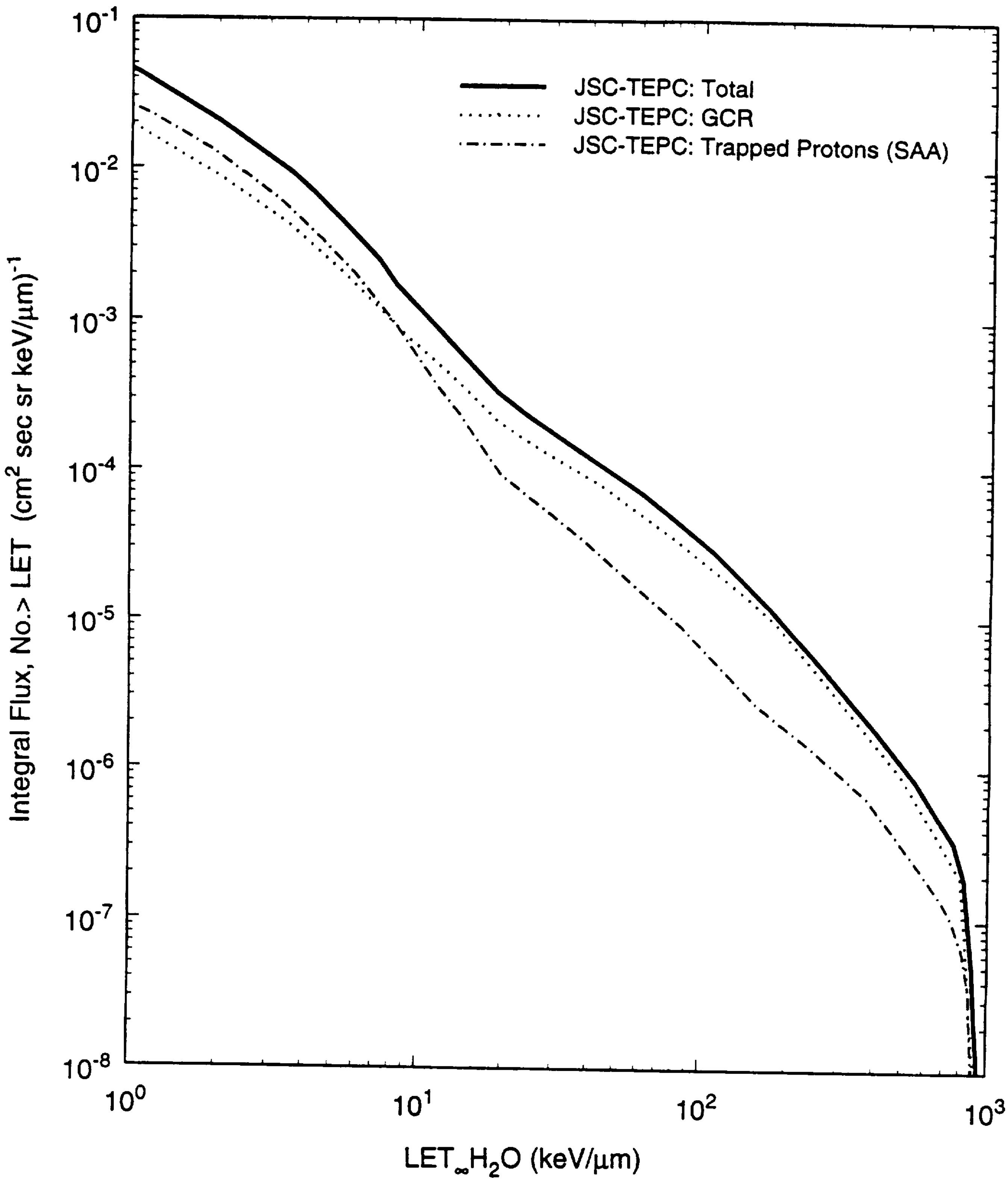


Figure 3-8. Trapped Proton (SAA), GCR and Total LET Spectra measured by the JSC-TEPC inside the Mir Core Module during the NASA-2/Mir-21 mission[27].

Chapter 4 – Measurements of Absorbed Dose using Passive Detectors on Mir

4.1 PASSIVE RADIATION EXPERIMENTS ON THE MIR

Over the approximately 12 year lifetime of the Russian Mir Space Station a large amount of data on the radiation environment, both inside and outside the station has been obtained using passive radiation detectors. A variety of different types of TLDs from a number of different institutions have been used to measured total dose and mean dose rate. Plastic nuclear track detectors (PNTDs) from at least four different countries have been used to measure LET spectra above 5 keV/μm. A variety of methods have been employed to attempt the measurement of the neutron energy spectrum inside Mir. These include photographic nuclear emulsions, combinations of fission foils and other neutron sensitive materials and PNTDs, and bubble detectors. Table 4-1 presents an overview of the different types of passive detectors that have been used on Mir throughout its operational life. Much of this data has only been recently made available—some at the 3rd Workshop on Radiation Monitoring for the International Space Station held in Budapest, Hungary in March, 1998, and some at the 1998 COSPAR in Nagoya, Japan in July, 1998.

This chapter will concentrate on results from TLD measurements of total dose and mean dose rate made inside the Core Module of the Mir station. Because of their compact size and ease of use, TLDs are particularly well suited for the monitoring of radiation levels inside spacecraft and this has led to the accumulation of a large number of TLD dose measurements inside Mir. For a number of different reasons most of these measurements were carried out inside the Core Module of the Mir. The Core Module is the largest module of the Mir Space Station and is that module in which the crew spends the majority of its time. The Core Module was the first module of the Mir to be launched. It is also structurally similar to the main Russian module of the International Space Station. Finally, a shielding model of the Core Module has been developed and shielding values for a number of specific locations inside the Mir have been calculated. These shielding values can be incorporated into model calculations of dose rate inside the Core. The results reported in this chapter are first presented by institution and then are presented by location inside the Core Module. These mean dose rate measurements provide a basis for comparison with model calculations of dose rate made at the same shielding location and at a similar time in the solar epoch.

Table 4-1. Passive Radiation Experiments carried out aboard the Russian Mir Space Station since its launch in 1986.

Passive Detector	Investigator/Institution/Nation	Measured Quantity
TLDs	Akatov/IMBP/Moscow, Russia Schoner/ISDA/Vienna, Austria Deme/Atmoki/Budapest, Hungary Benton/USF/San Francisco, USA Badhwar/JSC/Houston, USA Reitz/DLR/Koln, Germany	Total Absorbed Dose Mean Dose Rate
Plastic Nuclear Track Detectors	Benton/USF/San Francisco, USA Marenny/ISRS/Moscow, Russia Kushin/IMBP/Moscow, Russia Heinrich/UoS/Siegen, Germany Beaujean/UoK/Kiel, Germany Doke/NASDA/Tokyo, Japan Yasuda/NIRS/Chiba, Japan	Linear Energy Transfer Spectra, Dose, Dose Equivalent Spectra > 5 keV/μm
Nuclear Emulsions	Dudkin/ISRS/Moscow, Russia	High Energy Neutrons
LiF/CR-39	Benton/USF/San Francisco, USA	Low Energy Neutrons
CR-39	PTB/Braunschweig, Germany	Low Energy Neutrons
Bubble Detectors	Ing/BTI/Chalk River, Canada	Low Energy Neutrons

Abbreviations:

IMBP	Institute of Biomedical Problems
ISDA	Institute of Space Dosimetry, Austria
Atomki	Hungarian Atomic Energy Institute
USF	University of San Francisco
JSC	Johnson Space Center
DLR	Deutsches Zentrum fur Luft- und Raufahrt
ISRS	Institute for Spacecraft Radiation Safety
UoS	University of Siegen
UoK	University of Kiel
NASDA	National Space Development Agency
NIRS	National Institute of Radiological Studies
PTB	Physikalisch-Technische Bundesanstalt
BTI	Bubble Technologies, Inc.

4.2 ABSORBED DOSE MEASUREMENTS BY INSTUTUTE

4.2.1 Institute of Biomedical Problems, Russia

The Institute of Biomedical Problems, Moscow, is responsible for dosimetry and radiation risk assessment for the Russian Cosmonaut Corp. The Space Radiation Safety Department within IMBP has had a long-term dosimetric program utilizing TLDs both as part of Crew Passive Dosimeters that are to be constantly worn by the cosmonauts during space flight, and in monitoring absorbed dose in specific locations within the spacecraft over an extended period of time. Currently the IMBP is using commercially available TLD-600 and TLD-700 and utilize a standard Harshaw reader for analysis. While TLD dose measurements have been made by IMBP over nearly the entire duration of the Mir program, only a small fraction of this data has been published. Usually the measurements that have been made available are those made in conjunction with another institute for purposes of comparison. Two examples of this include data from the DosiMir 1 and 2 experiments in 1991, and the ADLET-1, -2, and –3 experiments in 1994, shown in Table 4-2 carried out in collaboration with the Institute of Space Dosimetry, Austria, and with the University of San Francisco as part of the NASA/Mir Science Program, shown in Table 4-6 [28].

4.2.2 Institute of Space Dosimetry, Austria

The Institute of Space Dosimetry (ISDA), Vienna, Austria, has carried out a number of experiments aboard the Mir to measure absorbed dose. These include the DosiMir 1 an 2 experiments in 1991 (Table 4-2), the ADLET 1, 2, and 3 experiments in 1994 (Table 4-2) and measurements during the Mir-19 mission in 1995 (Table 4-10). ISDA has developed a technique to extract not only total absorbed dose from TLDs, but also average LET. Based on these average LET results, a Quality Factor (Q) is determined and a value for Dose Equivalent (H) is derived. An assessment of the accuracy of this technique is beyond the scope of this report and only dose and mean dose rate results are presented herein [28].

4.2.3 Deutsches Zentrum fur Luft –und Raumfahrt e.V., Germany

The space radiation safety and dosimetry program of the Deutsches Zentrum fur Luft –und Raumfahrt e.V. (DLR), Koln, Germany, serves as the coordinating agency for different German research groups carrying out space radiation measurements as well as conducting its own TLD-based dosimetry program. DLR carried out a number of TLD measurements inside the Core Module of Mir in 1992 in collaboration with IMBP, in 1994 as part of the ESA EuroMir 94 mission, in 1995 in collaboration with ATOMKI as part of the ESA EuroMir 95 mission and in 1997, again in collaboration with IMBP.

Table 4-3 contains the mission averaged dose rate for DLR TLDs inside the Core Module for these four missions, along with results from the ATOMKI Pille TLD bulbs deployed in the same locations during the EuroMir 95 mission. Differences in the DLR and Pille results from EuroMir 95 probably stem from differences in the type of TL material used. DLR uses standard Harshaw TLD-700 (^{7}LiF) and TLD-600 (^{6}LiF), while the Pille TLDs consist of $CaSO_4$:Dy and LiF:Mg,Ti. The differences in the measurements, made at the same time and under nearly-identical shielding conditions, give an indication of the spread in dose rate measurements to be expected from different TL materials and different TLD readers and readout protocols [29].

Table 4-2. Doses and dose rates measured by the Institute for Space Dosimetry, Austria (ISDA) and the Institute for Biomedical Problems, Moscow (IMBP) inside the Core Module of the Russian Mir Space Station[28].

Location		DosiMir 1 5/91 – 10/91 145 d	DosiMir 2 10/91 8 d	ADLET-1 1/94 – 7/94 182 d	ADLET-2 1/94 – 11/94 300 d	ADLET-3 1/94 – 3/95 437 d
Commander's Cabin, ISDA	Dose Dose Rate	34.8 ± 1.2 mGy 240 ± 8 μGy/d	1.6 ± 0.2 mGy 201 ± 3 μGy/d	55.0 ± 1.8 mGy 302 ± 10 μGy/d	90.3 ± 3.0 mGy 301 ± 10 μGy/d	125.9 ± 4.4 mGy 288 ± 10 μGy/d
Commander's Cabin, IMBP	Dose Dose Rate		1.7 ± 0.1 mGy 218 ± 10 μGy/d	59.2 ± 4.9 mGy 325 ± 27 μGy/d	83.4 ± 5.1 mGy 278 ± 17 μGy/d	130.7 ± 9.2 mGy 299 ± 21 μGy/d
End of Core Module, ISDA	Dose Dose Rate			37.3 ± 1.8 mGy 205 ± 10 μGy/d	70.8 ± 6.0 mGy 236 ± 20 μGy/d	96.1 ± 4.4 mGy 220 ± 10 μGy/d
End of Core Module, IMBP	Dose Dose Rate			37.1 ± 3.1 mGy 204 ± 17 μGy/d	69.6 ± 4.2 mGy 232 ± 14 μGy/d	100.1 ± 4.4 mGy 229 ± 10 μGy/d

Table 4-3. DLR Dose Rates measured with TLD-700 on four Mir missions inside the Core module. The Pille TLD-Reader was included on the EuroMir 95 mission and dose rates are presented for comparison[29].

	Dose Rate (µGy/d)				
Dosimeter Location	Mir 92	EuroMir 94	EuroMir 95	Pille 95	Mir 97
Panel 132, Floor beneath work table	184 ± 6 181 ± 5	236 ± 3 234 ± 7	245 ± 3 236 ± 2	302 ± 7	
Panel 432, Right Wall beneath work table	191 ± 10 183 ± 8	255 ± 5 253 ± 5	248 ± 2 236 ± 11	291 ± 9	
Panel 117, Right Floor in small diameter	215 ± 9 241 ± 11	353 ± 9 293 ± 6	345 ± 4 297 ± 5	336 ± 12	344 ± 4 307 ± 6
Panel 329, Left Wall near Commander's cabin	178 ± 6 191 ± 4	261 ± 5 253 ± 4	237 ± 3 244 ± 6	295 ± 12	261 ± 6 249 ± 3
Flight Engineer's Cabin Level 4, near light # 2	205 ± 6 208 ± 5 229 ± 13 294 ± 13	380 ± 7 322 ± 4	483 ± 8 371 ± 3	247 ± 10	461 ± 4 370 ± 3
Personal — wrist — waist			245 ± 8 245 ± 5	247 ± 3	270 ± 5

4.2.4 KFKI Atomic Energy Research Institute, Hungary

The KFKI Atomic Energy Research Institute (ATOMKI), Budapest, Hungary, has developed a portable TLD system including encapsulated TLDs and a Reader for use on board spacecraft. The "Pille" TLD system has been used aboard Russian space stations since the Salyut 6 mission in 1980. The current version, Pille95s, is currently deployed aboard the Mir station and is planned to be deployed aboard both the Russian and American portions of the International Space Station. The Pille system consists of a number of $CaSO_4$:Dy and LiF:Mg,Ti thermoluminescent bulb dosimeters and a portable microprocessor-based reader. The system is capable of a precision of 0.1 µGy and possesses the ability to make automatic corrections for individual dosimeter sensitivity and temperature dependence. The system includes a PCMCIA memory card for storage of dose, date, time, dosimeter number, and glow curve data. The Pille95s reader and one of the TLD bulbs are pictured in Figure 4-1. The Pille95s system was used aboard Mir during the Euromir 95 mission and more recently during the NASA-4/Mir-23 mission, including during EVA. Table 4-3 contains average mission dose rate measurements made during the EuroMir 95 mission by the Pille system along with dose rates measured by DLR using TLDs positioned in the same locations. Table 4-4 presents the dose and dose rate measurements carried out using the Pille system during the EuroMir 95 mission[30].

Table 4-4. Doses and Dose Rates measured by the Pille TLD System on EuroMir-95[30].

Exposure		duration	Dosimeter no.												mean µGy/d
			1		2		3		4		5		6		
start m.d h:min	end m.d h:min	hours	dose µGy	d.rate µGy/d	dose µGy	d.rate µGy/d	dose µGy	d.rate µGy/d	dose µGy	d.rate µGy/d	dose µGy	d.rate µGy/d	dose µGy	d.rate µGy/d	
10.25 23:20	11.01 16:15	161	2080	310	2090	312	2290	241	2120	314	1640	245	1930	295	302
11.01 16:15	11.08 18:05	170	2200	310	2090	295	2290	322	2120	298	1640	230	1930	271	286
11.08 18:05	11.15 21:26	171	2190	307	1960	274	2500	350	1970	276	1760	247	1800	252	286
11.15 21:26	11.22 14:25	161	2060	307	1680	250	2140	319	1970	293	1650	245	1860	276	281
11.22 14:25	11.29 13:00	167	2000	288	1940	278	2370	341	2050	293	1830	262	2050	293	290
11.29 13:00	12.04 20:09	127	1580	298	1490	281	1830	246	1550	293	1330	250	1500	283	290
Mean ± σ				302 ± 7		282 ±19		336 ± 12		293 ± 12		247 ± 10		278 ± 14	290 ± 26

The Pille TLD system was also flown as part of the NASA-4/Mir-23 mission and TLD bulbs were carried by the cosmonauts and astronauts during EVA. Table 4-12 presents dose rate results from the 7 TLD bulbs flown during the NASA-4 mission while Table 4-13 gives dose results measured during EVA. Average dose rate measured inside the Mir by the Pille system during the NASA-4 mission was 325 ± 26 µGy/d and the spread in dose rate between highest and lowest was nearly a factor of two. Dose measured outside the Mir during EVA ranged from 2.5 to 2.8 times that measured on the inside during the same period of time.

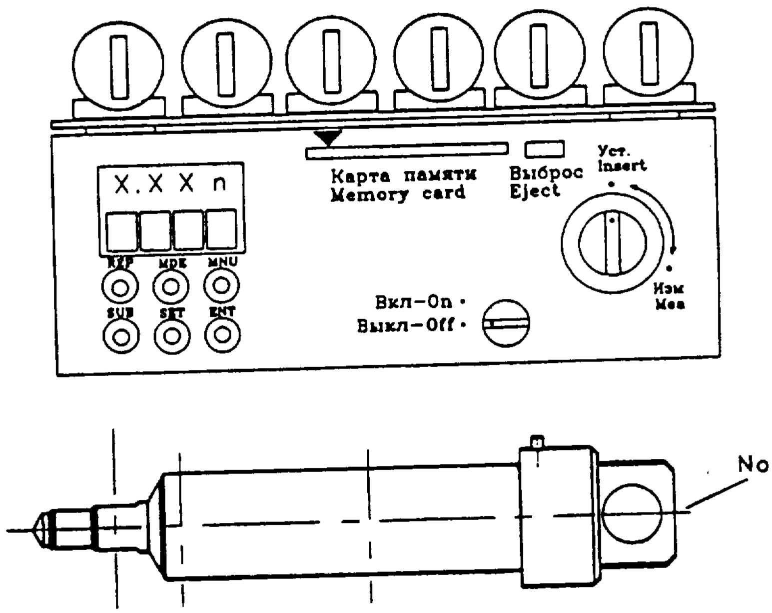


Figure 4-1. The Pille 95s reader and TLD bulb used aboard the Mir[30].

4.2.5 University of San Francisco

A series of passive integrating measurements of environmental radiation using passive dosimeters located both inside and outside the Mir Space Station were carried out as part of the NASA-Mir Phase 1B Science Program. The experiment was a combined project of the University of San Francisco Physics Department and Eril Research, Inc. Total absorbed dose is being measured using thermoluminescent detectors (TLDs) included inside each of six Area Passive Dosimeters located throughout the interior of the Mir Station. The use of TLDs, and specifically TLD-700 (^{7}LiF) to measure absorbed dose has become standard on missions of the U. S. Space Shuttle. APDs similar to those deployed aboard Mir during the NASA/Mir Phase-1B Science Program have been included on several Space Shuttle missions since the inception of the program. These dosimeters have also been used aboard the Long Duration Exposure Facility, the ESA Eureca retrievable spacecraft, numerous Russian/Soviet Biocosmos missions and aboard Mir itself during the Mir-18 mission.

Table 4-5 shows the dose rates and dose equivalent rates measured using TLDs for each of the six APDs exposed during each of three NASA/Mir missions. Table 4-6 shows the dose and dose rate measured in CR-39 during the NASA-2 mission for particles of LET ≥5 keV/μm. Table 4-7 shows USF NASA-2 dose and dose rates from TLDs after having been corrected for the high-LET particle component, while Table 4-8 presents the total (low and high LET) dose and dose rates measured by USF TLDs during the NASA-2 mission[26]. During the NASA-2/Mir-21 mission dose rates varied from 268 μGy/d for APD-6 in the Kvant 2 module to 422 μGy/d for APD-3 at the base of the control console in the Core module. The average dose rate for each of the five APDs returned by STS-79 was 324 μGy/d. Similarly, dose equivalent rate varied from 513 μSv/d in APD-6 to 710 μSv/d in APD-3. It should be noted that the dose equivalent rate measurements were determined using results from both the TLDs and PNTDs and thus represent a corrected total dose equivalent rate while the dose rates reported here are only from the measurements made in TLDs and thus underreport the dose contribution from high (>5 keV/μm) LET particles.

Table 4-5 also includes dose rates measured at the six APD locations during the NASA-3/Mir-22 and NASA-4/Mir-23 missions. Dose equivalent rates are presently not available and are awaiting completion of the PNTD analysis for these two missions. Dose rate for the NASA-3/Mir-22 mission ranged from 265 μGy/d in APD-6 to 378 μGy/d in APD-3. Dose rate for the NASA-4/Mir-22 mission ranged from 273 μGy/d in APD-5 located on the EVA airlock bulkhead in the Kvant-2 module to 361 μGy/d for APD-3[26]. Shielding differences in the six APD locations are immediately apparent with APD-3, in the Core module beneath the command console, being under the lowest shielding and APD-6, on ceiling panel #303 in the Kvant 2 module, being under greatest shielding. The APD-6 location is surrounded by a large amount of equipment and is located immediately beneath the two gyrodynes atop which the EDA was mounted. The other conclusion that can be drawn from Table 4-5 is that dose rates decreased for each of the successive NASA/Mir missions. The most likely reason for this a decrease in altitude of the Mir Station during this time period. Dose rate decreases exponentially with decreasing altitude in the South Atlantic Anomaly. Due to atmospheric drag, the Mir continually loses altitude and must periodically be reboosted to a higher altitude. Records of when reboosts occurred and the altitude of Mir as a function of time are currently be consulted to verify this interpretation.

4.2.6 NASA Johnson Space Center

Doses in the Core Module of Mir were also measured using TLDs provided by the NASA Johnson Space Center during the NASA/Mir Science Program. Table 4-9 presents results measured by JSC TLDs during the NASA-2/Mir-21 and NASA-3/Mir-22 missions. Like USF, JSC uses Harshaw TLD-700 (^{7}LiF) TLDs. The locations and thus the local shielding of the JSC TLDs were somewhat different than the USF TLDs, leading to differences in measured dose rate. Dose rate between JSC TLDs varied by nearly a factor of two, while the spread in dose rates measured by USF was only of the order of 40%. The mean dose rate measured inside the Core Module by the JSC TLDs during the NASA-2 mission was 333 ± 4 μGy/d, and during the NASA-3 mission was 327 ± 4 μGy/d [27].

Table 4-5. Doses and Mean Dose Rates measured inside the Mir Space Station Core Module and Kvant 2 modules by USF during the NASA/Mir Phase 1B Science Program. Also included are doses and dose rates measured at the same location during the Mir-21/NASA-2 mission by IMBP[26,28].

Detector	Location		Mir-21 /NASA-2 3/22/96 – 9/26/96 188.2 days	IMBP Results Mir-21/NASA-2 TLD-700	IMBP Results Mir-21/NASA-2 TLD-600	Mir-22/NASA-3 9/16/96 – 1/22/97 127.2 days	Mir-23/NASA-4 1 /12/97 – 5/22/97 130.1 days
APD-1	Core Module	Dose	67.1 ± 1.9 mGy	74.2 ± 2.1 mGy	75.7 ± 1.9 mGy	39.3 ± 1.2 mGy	42.0 ± 1.3 mGy
	Door to Engineer's Cabin	Dose Rate	328 ± 10 μGy/d	396 ± 11 μGy/d	402 ± 10 μGy/d	309 ± 9 μGy/d	323 ± 1.0 μGy/d
APD-2	Core Module	Dose	54.2 ± 1.6 mGy	65.3 ± 0.8 mGy	68.7 ± 2.3 mGy	34.8 ± 1.0 mGy	37.3 ± 1.1 mGy
	Ceiling Panel #325	Dose Rate	288 ± 9 μGy/d	347 ± 4 μGy/d	365 ± 12 μGy/d	273 ± 8 μGy/d	287 ± 8 μGy/d
APD-3	Core Module, beneath	Dose	76.6 ± 2.4 mGy	93.2 ± 1.7 mGy	91.1 1.5 mGy	48.2 ± 1.5 mGy	47.0 ± 1.5 mGy
	Command Console	Dose Rate	407 ± 13 μGy/d	495 ± 9 μGy/d	484 ± 8 μGy/d	378 ± 12 μGy/d	361 ± 11 μGy/d
APD-4	Adaptor Module	Dose	60.8 ± 1.9 mGy	67.9 ± 1.3 mGy	70.2 ± 1.3 mGy	2.47 ± 0.1 mGy†	39.1 ± 1.2 mGy
	near Window #14.	Dose Rate	324 ± 10 μGy/d	361 ± 7 μGy/d	373 ± 7 μGy/d	243 ± 7 μGy/d†	300 ± 9 μGy/d
APD-5	Kvant 2	Dose	3.23 ± 0.1 mGy*	86.2 ± 1.9 mGy*	85.3 ± 1.1 mGy*	128.6 ± 3.9 mGy‡	67.6 ± 2.9 mGy**
	Airlock bulkhead	Dose Rate	319 ± 10 μGy/d*	458 ± 10 μGy/d*	453 ± 6 μGy/d*	421 ± 13 μGy/d‡	273 ± 8 μGy/d**
APD-6	Kvant 2	Dose	51.1 ± 1.6 mGy	58.5 ± 1.1 mGy	60.0 ± 0.9 mGy	33.7 ± 1.0 mGy	76.3 ± 2.3 mGy††
	Ceiling Panel #303	Dose Rate	271 ± 9 lμGy/d	311 ± 6 μGy/d	319 ± 5 μGy/d	265 ± 8 μGy/d	285 ± 8 μGy/d

*Flight Movement APD (STS-79) exposed for 10 days.
†Flight Movement APD (STS-81) exposed for 10 days.
‡Exposed for 305.3 days on both NASA-2 and NASA-3 missions.
**Exposed for 247.4 days on both NASA-3 and NASA-4 missions.
††Exposed for 267.5 days on both NASA-4 and NASA-5 missions.

Table 4-6. Dose and Dose Equivalent Rates from particles with LET ≥5 keV/μm measured in CR-39 PNTDs measured by USF aboard the Mir Station during the NASA-2/Mir-21 mission[26].

APD No.	Dose Rate (LET ≥5 keV/μm) (μGy/d)	Dose Equivalent Rate (LET ≥5 keV/μm) (μSv/d)
1	26.3 ± 1.2	267 ± 18
2	29.7 ± 0.9	284 ± 12
3	31.9 ± 0.8	326 ± 11
4	38.0 ± 1.0	345 ± 14
6	31.4 ± 0.8	265 ± 9

Table 4-7. Doses measure by TLDs, corrected TLD doses and corrected dose rates for the five NASA-2/Mir-21 USF APDs[26].

APD No.	TLD Dose (mGy)	Corrected Dose (mGy)	Corrected Dose Rate (μGy/d)
1	61.7 ± 1.9	63.1 ± 1.9	334 ± 10
2	54.2 ± 1.6	55.7 ± 1.6	295 ± 8
3	76.6 ± 2.4	78.3 ± 2.4	400 ± 12
4	60.8 ± 1.9	62.6 ± 1.9	320 ± 10
6	51.1 ± 1.6	52.5 ± 1.6	278 ± 9

Table 4-8. Total dose equivalent and dose equivalent rates for the five NASA-2/Mir-21 USF APDs[26].

APD No	Dose Equivalent (mSv)	Dose Equivalent Rate (μSv/d)
1	108.4 ± 0.4	576 ± 2
2	103.6 ± 0.3	551 ± 2
3	133.6 ± 0.3	710 ± 2
4	120.3 ± 0.3	639 ± 2
6	96.5 ± 0.2	513 ± 1

Table 4-9. Doses and dose rates measured by JSC in the Mir Core Module using TLD-700 during the NASA-2/Mir-21 and NASA-3/Mir-22 missions[27].

PRD Number	Location		Mir-21 /NASA-2 3/22/96 – 9/26/96 188.2 days	Mir-22/NASA-3 9/16/96 – 1/22/97 127.2 days
1	Flight Engineer's Cabin outer wall	Dose Dose Rate	73.5 ± 0.8 mGy 391 ± 4 μGy/d	43.6 ± 0.7 mGy 341 ± 4 μGy/d
2	End of Core Module near treadmill	Dose Dose Rate	60.4 ± 0.6 mGy 321 ± 3 μGy/d	32.5 ± 0.5 mGy 254 ± 3 μGy/d
3	Panel #325, ceiling near R-16	Dose Dose Rate	74.1 ± 0.8 mGy 394 ± 4 μGy/d	44.2 ± 0.5 mGy 346 ± 3 μGy/d
4	Commander's Cabin, outer wall, near window	Dose Dose Rate	96.8 ± 0.9 mGy 514 ± 5 μGy/d	53.9 ± 0.7 mGy 421 ± 4 μGy/d
5	Panel # 307, above Control Console	Dose Dose Rate	57.8 ± 0.6 mGy 307 ± 3 μGy/d	34.6 ± 0.7 mGy 270.6 ± 4 μGy/d
6	Adaptor Module, near Windows # 14	Dose Dose Rate		42.0 ± 0.8 mGy 327.8 ± 4 μGy/d

Table 4-10 Doses and dose rates measured by ISDA in the Mir Core Module during the Mir-19 mission using TLD-600 and TLD-700 during the period of 6/27/95 to 11/20/95 (145 d)[28].

Number	Location		TLD-600	TLD-700
1	Commander's Cabin	Dose Dose Rate	61.9 ± 1.4 mGy 427 ± 10 μGy/d	59.5 ± 1.1 mGy 410 ± 8 μGy/d
2	Engineer's Cabin	Dose Dose Rate	65.6 ± 2.9 mGy 452 ± 20 μGy/d	64.8 ± 4.7 mGy 447 ± 32 μGy/d
3	Large Diameter	Dose Dose Rate	50.5 ± 1.5 mGy 348 ± 10 μGy/d	46.4 ± 1.5 mGy 320 ± 10 μGy/d
4	Adaptor Module, near Window # 14	Dose Dose Rate	52.4 ± 0.9 mGy 361 ± 6 μGy/d	51.3 ± 2.0 mGy 354 ± 14 μGy/d
5	Panel # 307, above Control Console	Dose Dose Rate	53.2 ± 1.8 mGy 366.9 ± 12 μGy/d	51.5 ± 1.8 mGy 355 ± 12 μGy/d
6	Panel #325, ceiling near R-16	Dose Dose Rate	59.7 ± 1.6 mGy 411 ± 11 μGy/d	55.1 ± 2.1 mGy 380 ± 15 μGy/d

Table 4-11. Dose Rates measured by the Pille TLD System during the NASA-4/Mir-23 mission[30].

Date of Readout	Dose rate (μGy/h) for dosimeters no.						
	1A	2A	2B	3A	3B	4A	5A
13 Feb 1997	15.1	12.6	12.6	20.3	21.1	9.9	9.7
27 Feb 1997	15.6	11.7	11.5	19.3	19.2	10.0	8.2
15 Mar 1997	14.7	12.5	12.5	17.2	18.3	10.2	9.2
24 Mar 1997	14.5	10.0	10.4	17.7	19.0	10.1	8.7
07 Apr 1997	14.1	10.9	11.0	14.9	15.2	9.9	9.5
24 Apr 1997	17.2	10.8	11.0	18.8	18.7	10.2	8.7
29 Apr 1997	15.4	12.7				10.2	
06 May 1997	14.2	11.8	13.0	19.8	20.6	9.7	11.4
Mean Dose Rate (μGy/h)	15.1 ± 0.9	11.6 ± 0.9	11.7 ± 0.9	18.3 ± 1.7	18.9 ± 1.8	10.0 ± 0.2	9.3 ± 1.0
Mean Dose Rate (μGy/d)	362 ± 22	278 ± 22	281 ± 22	439 ± 41	454 ± 43	240 ± 5	223 ± 24

Table 4-12. EVA Doses and Dose Rates measured by the Pille TLD System during the NASA-4/Mir-23 mission[30].

Dosimeter	User Name	Readout (μGy)	Readout corrected with control (μGy)	Readout corrected with control and SAA influence (μGy)
1A	Vasili Tsibliev (V.T.)	415	349	386
2A	Jerry Linenger (J.L)	373	307	341
4A	Control (inside)	144	-	-

	Dose rate – inside (μGy/h)	Dose rate - V.T (μGy/h)	Ratio to inside - V.T.	Dose rate - J.L. (μGy/h)	Ratio to inside - J.L.	Mean EVA dose rate (μGy/h)	Mean ratio to inside
without SAA corrections	15.5	69.8	4.50	61.4	3.96	65.6	4.23
with SAA corrections	23.0	77.2	3.35	68.2	2.96	72.7	3.15

4.3 SHIELDING MODEL OF THE MIR CORE MODULE:

A shielding model of the Core Module of the Mir Station was developed by Russian specialists and the shielding probability at 9 locations inside the Core has been calculated[25]. This shielding model is less than ideal in a number of ways. First, it is a model only of the Core Module and does not include shielding effects from the other five modules that make up the final configuration of the Mir Space Station. Second, the model is for the Core as it was configured at the time of launch in June of 1986. It does not include shielding from the extensive amount of equipment and instrumentation that was later added over the lifetime of the station. Figure 4-2 shows the 9 shielding locations inside the Core Module for which calculations were made. Figures 4-3 and 4-4 shows the shielding probability for seven of the locations while Table 4-13 lists their spatial coordinates and mean shielding values. Figure 4-5 shows the shielding probability for the remaining two locations.

Table 4-13. Coordinates of Locations inside the Mir Core Module for which Shielding Distributions were Calculated. Origin (0,0,0) is located at the front of the adapter module, and the centerline of the station[25].

Location No.	Description	x (cm)	y (cm)	z (cm)	mean shielding (g/cm^2)
1	Commander's cabin, outer wall	945	40	190	18.6
2	Engineer's cabin, outer wall	945	40	-190	22
3	Panel # 307, above Command Console	291	88	0	53
4	Adapter Module, near Window # 14	80	0	72	38
5	Large Diameter, rear of Core Module	1121	112	-112	36
6	Panel #325, near R-16 Dosimeter	796	204	0	44
7	Small Diameter, centerline of Core	458	0	0	N/A

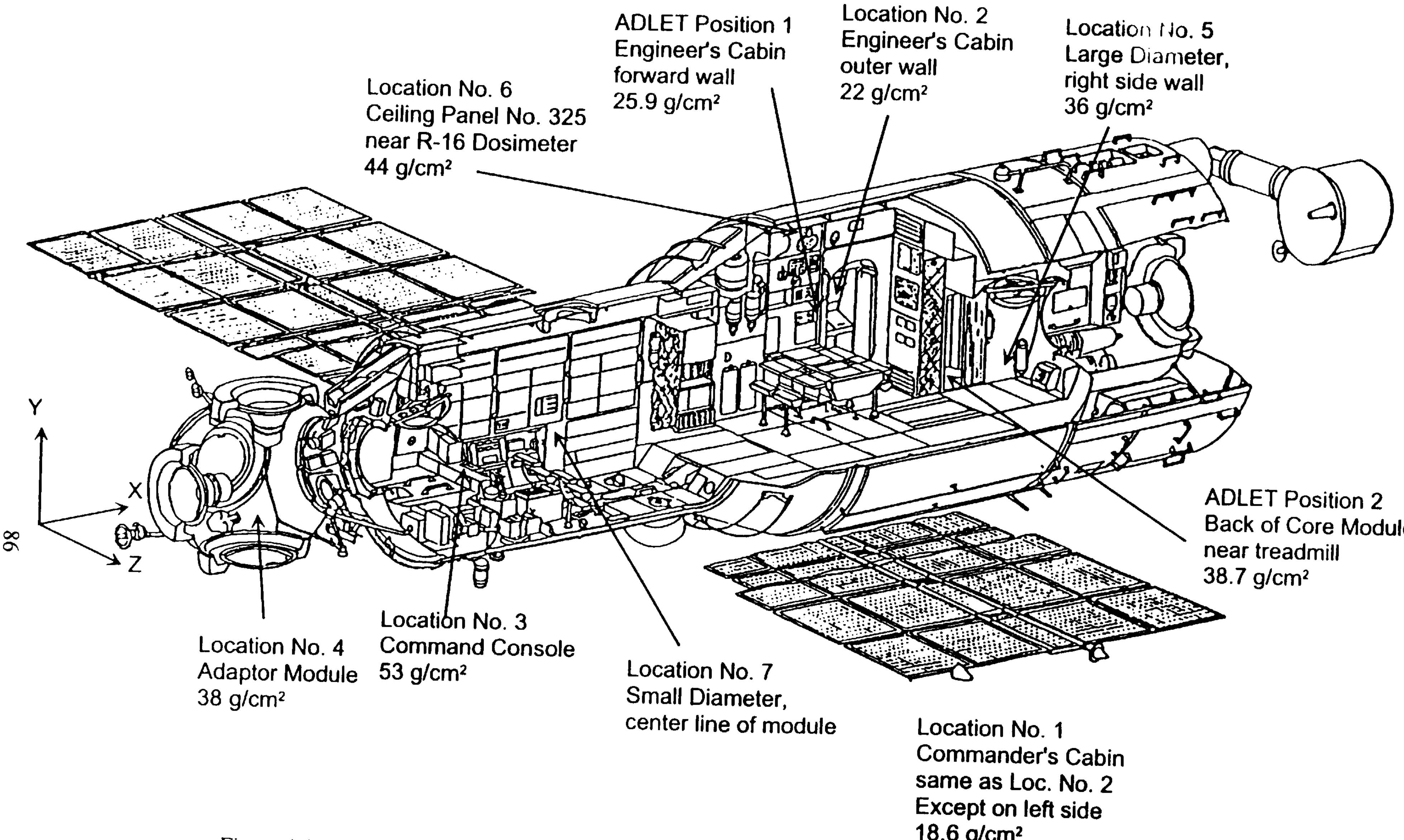


Figure 4-2. Positions of the 9 locations inside the Core Module of the Mir Orbital Station for which shielding probabilities were calculated[adapted from 25 & 28].

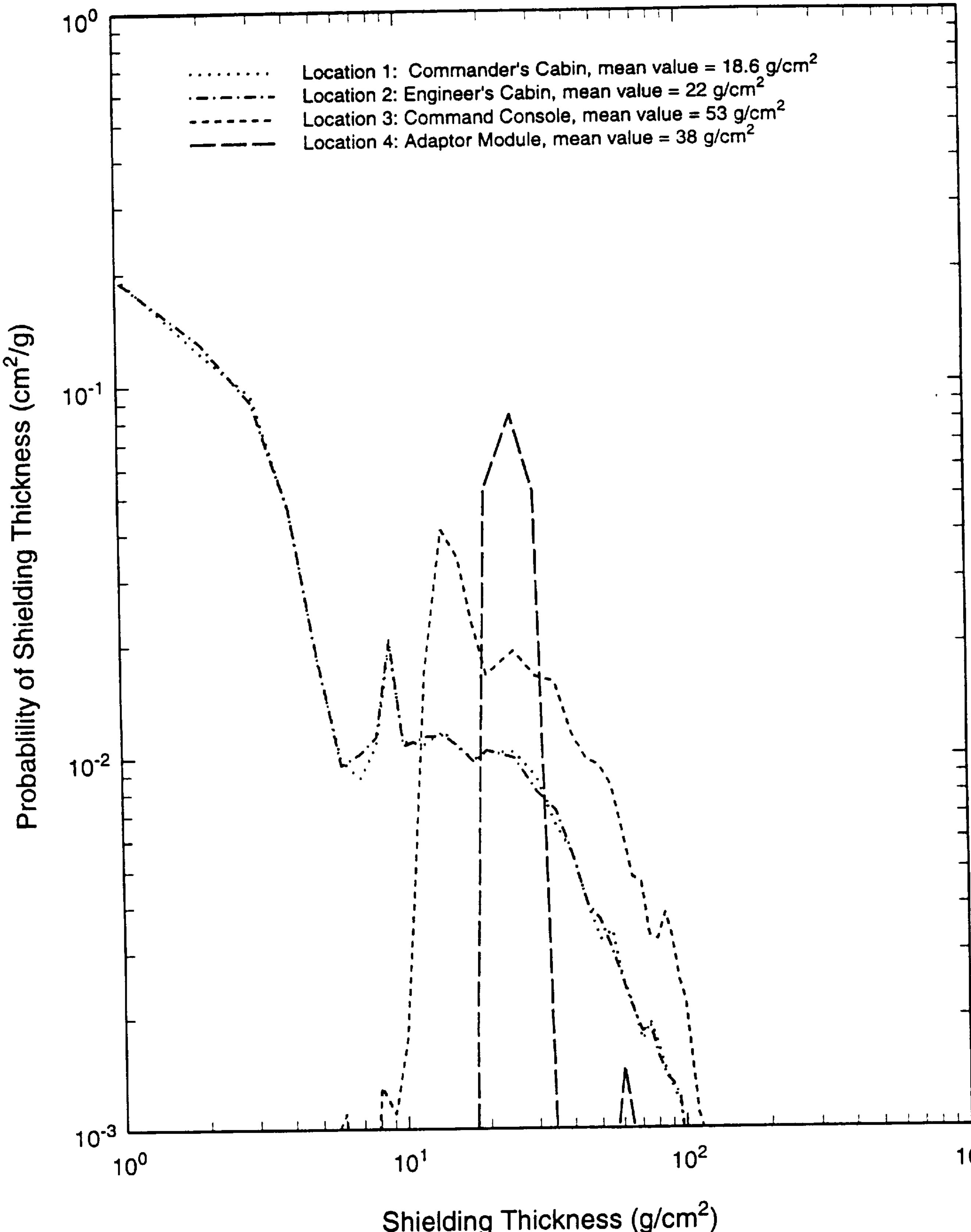


Figure 4-3. Calculated shielding probabilities for 4 locations inside the Mir Core Module[adapted from 25].

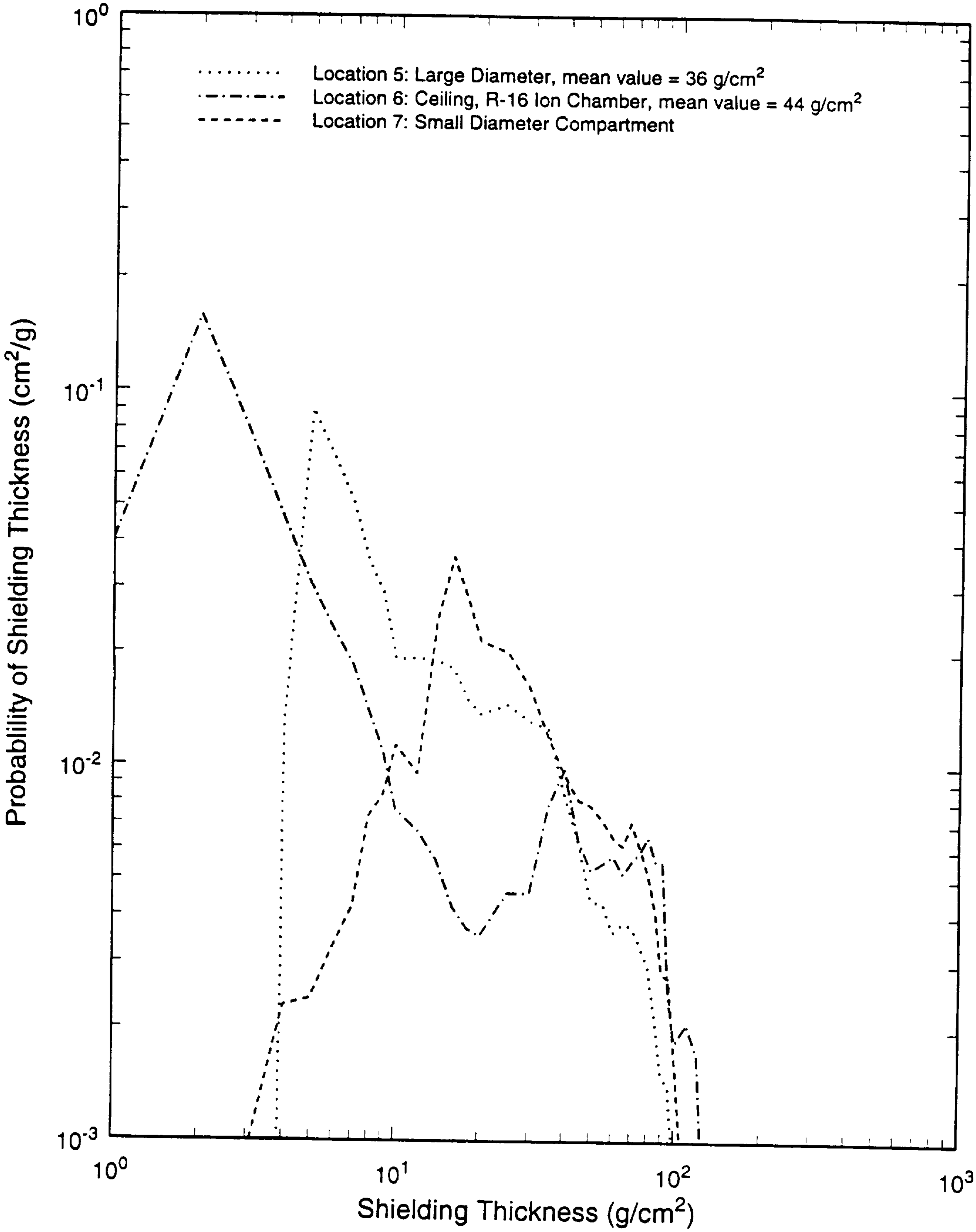


Figure 4-4. Calculated shielding probabilities for 3 locations inside the Mir Core Module[adapted from 25].

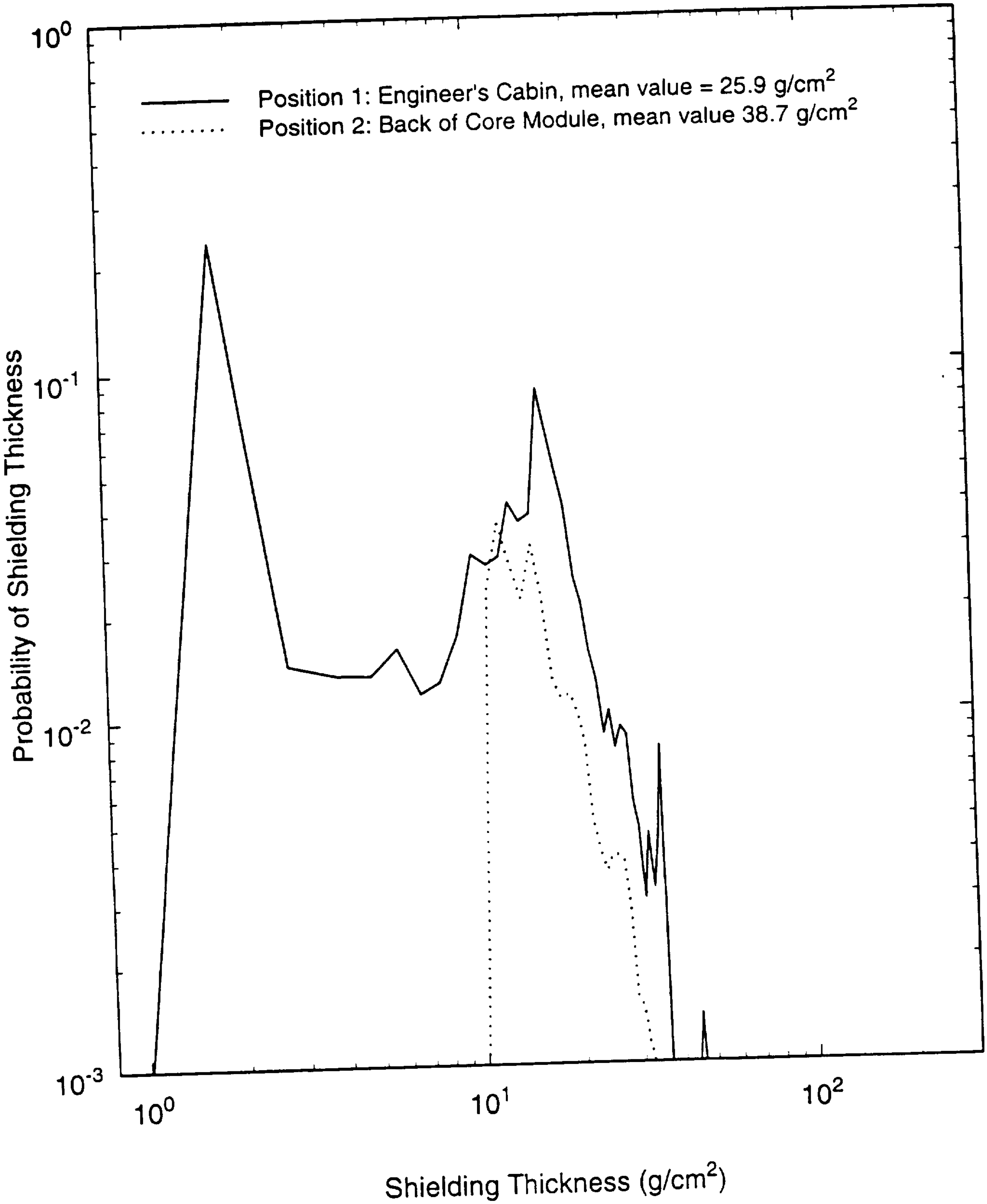


Figure 4-5. Calculated shielding probabilities for the two locations of the ADLET measurements inside the Mir Core Module[28].

4.4 DOSE RATE AT SPECIFIC SHIELDING LOCATIONS

Dose rate measured at seven of the locations at which shielding inside the Mir Core Module has been calculated are presented in the following tables. These measurements were made over differing durations ranging from days to months, and at very different times, sometimes separated by years. Differences in dose rates measured at a specific location thus reflect differences in the spacecraft altitude and attitude, solar cycle, and local shielding conditions as equipment is received and discarded. For example, the dose rate at Location No. 1 inside the Commander's cabin varied from 410 μGy/d in mid- to late-1995 to 514 μGy/d in mid-1996[27,28]. Similarly dose rate at Location No. 2 in the Flight Engineer's cabin varied from 201 μGy/d to 454 μGy/d, a difference of greater than a factor of 2, over a period lasting from May 1991 to May 1997.

Change in altitude is probably the single largest factor contributing to this difference in dose rate measured at the same location inside the Core Module over an extended period of time. Dose rate increases by roughly a factor of 2 for every 50 km increase in altitude. Since records of the altitude of the Mir Station as a function of time are, in principal, available, it should be possible to include altitude variation in any attempt to model the dose rate received inside Mir. Figures 4-6 and 4-7 show Mir altitude over two multi-year periods. A Progress tanker is used to boost Mir to a mean altitude of ~400 km on a periodic basis. Atmospheric drag then causes the Mir to slowly drop in altitude to a mean altitude of ~380 over the period of a year. At this time, Mir is once again boosted to an altitude in excess of 400 km.

Differences in the attitude of Mir and in the local shielding environment present at a given location are harder to model. Data of Mir's attitude with respect to the Sun is not readily available and it is not know whether records of this parameter have been maintained over the life of the station. The shielding environment inside the station is constantly changing. Over the course of it's history, the Mir has been expanded from the single Core Module to a complex consisting of six separate modules. In addition, much of the scientific research carried out aboard Mir has be centered in the Core Module. This means that much equipment is constantly being moved into and out of the volume near the nine Core Module locations for which shielding was calculated.

Table 4-14. Location No. 1: Commander's Cabin, outer wall, mean shielding = 18.6 g/cm^2[27,28].

Experiment/ Institution	Dates	Duration (days)	Dose (mGy)	Dose Rate (μGy/d)
Mir-19/ISDA TLD-600	6/27/95-11/20/95	145	61.9 ± 1.4	427 ± 10
Mir-19/ISDA TLD-700	6/27/95-11/20/95	145	59.5 ± 1.1	410 ± 8
NASA-2/JSC	3/22/96-9/26/96	188.2	96.8 ± 0.9	514 ± 5
NASA-3/JSC	9/16/96-1/22/97	127.2	53.9 ± 0.7	421 ± 4

Table 4-15. Location No. 2: Engineer's Cabin, outer wall, mean shielding = 22 g/cm^2 and ADLET Position 1: forward wall of Engineer's cabin, mean shielding = 25.9 g/cm^2[27,28,29,30]

Experiment/ Institution	Dates	Duration (days)	Dose (mGy)	Dose Rate (μGy/d)
DosiMir 1/ISDA	5/91 – 10/91	145	34.8 ± 1.2	240 ± 8
DosiMir 2/ISDA	10/91	8	1.6 ± 0.2	201 ± 3
DosiMir 2/IMBP	10/91	8	1.7 ± 0.1	218 ± 10
Mir 92/DLR	92			205 ± 6 208 ± 5 229 ± 13 294 ± 13
ADLET-1/ISDA	1/94 – 7/94	182	55.0 ± 1.8	302 ± 10
ADLET-1/IMBP	1/94 – 7/94	182	59.2 ± 4.9	325 ± 27
EuroMir 94/DLR	1994			380 ± 7 322 ± 4
ADLET-2/ISDA	1/94 – 11/94	300	90.3 ± 3.0	301 ± 10
ADLET-2/IMBP	1/94 – 11/94	300	83.4 ± 5.1	278 ± 17
ADLET-3/ISDA	1/94 – 3/95	437	125.9 ± 4.4	288 ± 10
ADLET-3/IMBP	1/94 – 3/95	437	130.7 ± 9.2	299 ± 21
EuroMir 95/DLR	1995			483 ± 8 371 ± 3
NASA-2/JSC	3/22/96-9/26/96	188.2	73.5 ± 0.8	391 ± 4
Mir-19/ISDA TLD-600	6/27/95-11/20/95	145	65.6 ± 2.9	452 ± 20
Mir-19/ISDA TLD-700	6/27/95-11/20/95	145	6408 ± 4.7	447 ± 32
Pille 95/Atomki	1995			247 ± 10
Mir 97/DLR	1997			461 ± 4 370 ± 3
NASA-3/JSC	9/16/96-1/22/97	127.2	43.6 ± 0.7	341 ± 4
NASA-4/Atomki	1/12/97-5/22/97	130.1	57.1 ± 5.3 59.1 ± 5.6	439 ± 41 454 ± 43

Table 4-16. Location No. 3: Command Console, mean shielding = 53 g/cm^2[27,28].

Experiment/ Institution	Dates	Duration (days)	Dose (mGy)	Dose Rate (μGy/d)
Mir-19/ISDA TLD-600	6/27/95-11/20/95	145	53.2 ± 1.8	366.9 ± 12
Mir-19/ISDA TLD-700	6/27/95-11/20/95	145	51.5 ± 1.8	355 ± 12
NASA-2/JSC	3/22/96-9/26/96	188.2	57.8 ± 0.6	307 ± 3
NASA-3/JSC	9/16/96-1/22/97	127.2	34.6 ± 0.7	270.6 ± 4

Table 4-17. Location 4: Adaptor module, near Window #14, mean shielding = 38 g/cm^2[26,27,28].

Experiment/ Institution	Dates	Duration (days)	Dose (mGy)	Dose Rate (μGy/d)
Mir-19/ISDA TLD-600	6/27/95-11/20/95	145	52.4 ± 0.9	361 ± 6
Mir-19/ISDA TLD-700	6/27/95-11/20/95	145	51.3 ± 2.0	354 ± 14
NASA-2/USF	3/22/96-9/26/96	188.2	60.8 ± 1.9	324 ± 10
NASA-2/IMBP TLD-600	3/22/96-9/26/96	188.2	67.9 ± 1.3	361 ± 7
NASA-2/IMBP TLD-700	3/22/96-9/26/96	188.2	70.2 ± 1.3	373 ± 7
NASA-3/JSC	9/16/96-1/22/97	127.2	42.0 ± 0.8	327.8 ± 4
NASA-4/USF	1/12/97-5/22/97	130.1	39.1 ± 1.2	300 ± 9

Table 4-18. Location 5: Large Diameter portion of Core Module, mean shielding = 36 g/cm^2[28].

Experiment/ Institution	Dates	Duration (days)	Dose (mGy)	Dose Rate (μGy/d)
Mir-19/ISDA TLD-600	6/27/95-11/20/95	145	50.5 ± 1.5	348 ± 10
Mir-19/ISDA TLD-700	6/27/95-11/20/95	145	46.4 ± 1.5	320 ± 10

Table 4-19. Location 6: Ceiling Panel No. 325 near R-16 Operational Dosimeter, mean shielding = 44 g/cm^2[26,27,27].

Experiment/ Institution	Dates	Duration (days)	Dose (mGy)	Dose Rate (μGy/d)
Mir-18/USF	2/28/95-7/7/95	129	34.0 ± 0.7	264 ± 5
Mir-19/ISDA TLD-600	6/27/95-11/20/95	145	59.7 ± 1.6	427 ± 10
Mir-19/ISDA TLD-700	6/27/95-11/20/95	145	55.1 ± 1.1	410 ± 32
NASA-2/USF	3/22/96-9/26/96	188.2	54.2 ± 1.6	288 ± 9
NASA-2/IMBP TLD-600	3/22/96-9/26/96	188.2	65.3 ± 0.8	347 ± 4
NASA-2/IMBP TLD-700	3/22/96-9/26/96	188.2	68.7 ± 2.3	365 ± 12
NASA-2/JSC	3/22/96-9/26/96	188.2	74.1 ± 0.8	394 ± 4
NASA-3/USF	9/16/96-1/22/97	127.2	34.8 ± 1.0	273 ± 8
NASA-3/JSC	9/16/96-1/22/97	127.2	44.2 ± 0.5	346 ± 3
NASA-4/USF	1/12/97-5/22/97	130.1	37.3 ± 1.1	287 ± 8

Table 4-20. ADLET Position 2: Back of Core Module near Treadmill, mean shielding = 38.7 g/cm^2[27,28].

Experiment/ Institution	Dates	Duration (days)	Dose (mGy)	Dose Rate (μGy/d)
ADLET-1/ISDA	1/94 – 7/94	182	37.3 ± 1.8	205 ± 10
ADLET-1/IMBP	1/94 – 7/94	182	37.1 ± 3.1	204 ± 17
ADLET-2/ISDA	1/94 – 11/94	300	70.8 ± 6.0	236 ± 20
ADLET-2/IMBP	1/94 – 11/94	300	69.6 ± 4.2	232 ± 14
ADLET-3/ISDA	1/94 – 3/95	437	96.1 ± 4.4	220 ± 10
ADLET-3/IMBP	1/94 – 3/95	437	100.1 ± 4.4	229 ± 10
NASA-2/JSC	3/22/96-9/26/96	188.2	60.4 ± 0.6	321 ± 3
NASA-3/JSC	9/16/96-1/22/97	127.2	32.5 ± 0.5	254 ± 3

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Table 4-17. Location 4: Adaptor module, near Window #14, mean shielding = 38 g/cm^2[26,27,28].

Experiment/ Institution	Dates	Duration (days)	Dose (mGy)	Dose Rate (μGy/d)
Mir-19/ISDA TLD-600	6/27/95-11/20/95	145	52.4 ± 0.9	361 ± 6
Mir-19/ISDA TLD-700	6/27/95-11/20/95	145	51.3 ± 2.0	354 ± 14
NASA-2/USF	3/22/96-9/26/96	188.2	60.8 ± 1.9	324 ± 10
NASA-2/IMBP TLD-600	3/22/96-9/26/96	188.2	67.9 ± 1.3	361 ± 7
NASA-2/IMBP TLD-700	3/22/96-9/26/96	188.2	70.2 ± 1.3	373 ± 7
NASA-3/JSC	9/16/96-1/22/97	127.2	42.0 ± 0.8	327.8 ± 4
NASA-4/USF	1/12/97-5/22/97	130.1	39.1 ± 1.2	300 ± 9

Table 4-18. Location 5: Large Diameter portion of Core Module, mean shielding = 36 g/cm^2[28].

Experiment/ Institution	Dates	Duration (days)	Dose (mGy)	Dose Rate (μGy/d)
Mir-19/ISDA TLD-600	6/27/95-11/20/95	145	50.5 ± 1.5	348 ± 10
Mir-19/ISDA TLD-700	6/27/95-11/20/95	145	46.4 ± 1.5	320 ± 10

Table 4-19. Location 6: Ceiling Panel No. 325 near R-16 Operational Dosimeter, mean shielding = 44 g/cm^2[26,27,27].

Experiment/ Institution	Dates	Duration (days)	Dose (mGy)	Dose Rate (μGy/d)
Mir-18/USF	2/28/95-7/7/95	129	34.0 ± 0.7	264 ± 5
Mir-19/ISDA TLD-600	6/27/95-11/20/95	145	59.7 ± 1.6	427 ± 10
Mir-19/ISDA TLD-700	6/27/95-11/20/95	145	55.1 ± 1.1	410 ± 32
NASA-2/USF	3/22/96-9/26/96	188.2	54.2 ± 1.6	288 ± 9
NASA-2/IMBP TLD-600	3/22/96-9/26/96	188.2	65.3 ± 0.8	347 ± 4
NASA-2/IMBP TLD-700	3/22/96-9/26/96	188.2	68.7 ± 2.3	365 ± 12
NASA-2/JSC	3/22/96-9/26/96	188.2	74.1 ± 0.8	394 ± 4
NASA-3/USF	9/16/96-1/22/97	127.2	34.8 ± 1.0	273 ± 8
NASA-3/JSC	9/16/96-1/22/97	127.2	44.2 ± 0.5	346 ± 3
NASA-4/USF	1/12/97-5/22/97	130.1	37.3 ± 1.1	287 ± 8

Table 4-15. Location No. 2: Engineer's Cabin, outer wall, mean shielding = 22 g/cm^2 and ADLET Position 1: forward wall of Engineer's cabin, mean shielding = 25.9 g/cm^2[27,28,29,30]

Experiment/ Institution	Dates	Duration (days)	Dose (mGy)	Dose Rate (μGy/d)
DosiMir 1/ISDA	5/91 – 10/91	145	34.8 ± 1.2	240 ± 8
DosiMir 2/ISDA	10/91	8	1.6 ± 0.2	201 ± 3
DosiMir 2/IMBP	10/91	8	1.7 ± 0.1	218 ± 10
Mir 92/DLR	92			205 ± 6 208 ± 5 229 ± 13 294 ± 13
ADLET-1/ISDA	1/94 – 7/94	182	55.0 ± 1.8	302 ± 10
ADLET-1/IMBP	1/94 – 7/94	182	59.2 ± 4.9	325 ± 27
EuroMir 94/DLR	1994			380 ± 7 322 ± 4
ADLET-2/ISDA	1/94 – 11/94	300	90.3 ± 3.0	301 ± 10
ADLET-2/IMBP	1/94 – 11/94	300	83.4 ± 5.1	278 ± 17
ADLET-3/ISDA	1/94 – 3/95	437	125.9 ± 4.4	288 ± 10
ADLET-3/IMBP	1/94 – 3/95	437	130.7 ± 9.2	299 ± 21
EuroMir 95/DLR	1995			483 ± 8 371 ± 3
NASA-2/JSC	3/22/96-9/26/96	188.2	73.5 ± 0.8	391 ± 4
Mir-19/ISDA TLD-600	6/27/95-11/20/95	145	65.6 ± 2.9	452 ± 20
Mir-19/ISDA TLD-700	6/27/95-11/20/95	145	6408 ± 4.7	447 ± 32
Pille 95/Atomki	1995			247 ± 10
Mir 97/DLR	1997			461 ± 4 370 ± 3
NASA-3/JSC	9/16/96-1/22/97	127.2	43.6 ± 0.7	341 ± 4
NASA-4/Atomki	1/12/97-5/22/97	130.1	57.1 ± 5.3 59.1 ± 5.6	439 ± 41 454 ± 43

Table 4-16. Location No. 3: Command Console, mean shielding = 53 g/cm^2[27,28].

Experiment/ Institution	Dates	Duration (days)	Dose (mGy)	Dose Rate (μGy/d)
Mir-19/ISDA TLD-600	6/27/95-11/20/95	145	53.2 ± 1.8	366.9 ± 12
Mir-19/ISDA TLD-700	6/27/95-11/20/95	145	51.5 ± 1.8	355 ± 12
NASA-2/JSC	3/22/96-9/26/96	188.2	57.8 ± 0.6	307 ± 3
NASA-3/JSC	9/16/96-1/22/97	127.2	34.6 ± 0.7	270.6 ± 4

Table 4-20. ADLET Position 2: Back of Core Module near Treadmill, mean shielding = 38.7 g/cm^2[27,28].

Experiment/ Institution	Dates	Duration (days)	Dose (mGy)	Dose Rate (µGy/d)
ADLET-1/ISDA	1/94 – 7/94	182	37.3 ± 1.8	205 ± 10
ADLET-1/IMBP	1/94 – 7/94	182	37.1 ± 3.1	204 ± 17
ADLET-2/ISDA	1/94 – 11/94	300	70.8 ± 6.0	236 ± 20
ADLET-2/IMBP	1/94 – 11/94	300	69.6 ± 4.2	232 ± 14
ADLET-3/ISDA	1/94 – 3/95	437	96.1 ± 4.4	220 ± 10
ADLET-3/IMBP	1/94 – 3/95	437	100.1 ± 4.4	229 ± 10
NASA-2/JSC	3/22/96-9/26/96	188.2	60.4 ± 0.6	321 ± 3
NASA-3/JSC	9/16/96-1/22/97	127.2	32.5 ± 0.5	254 ± 3

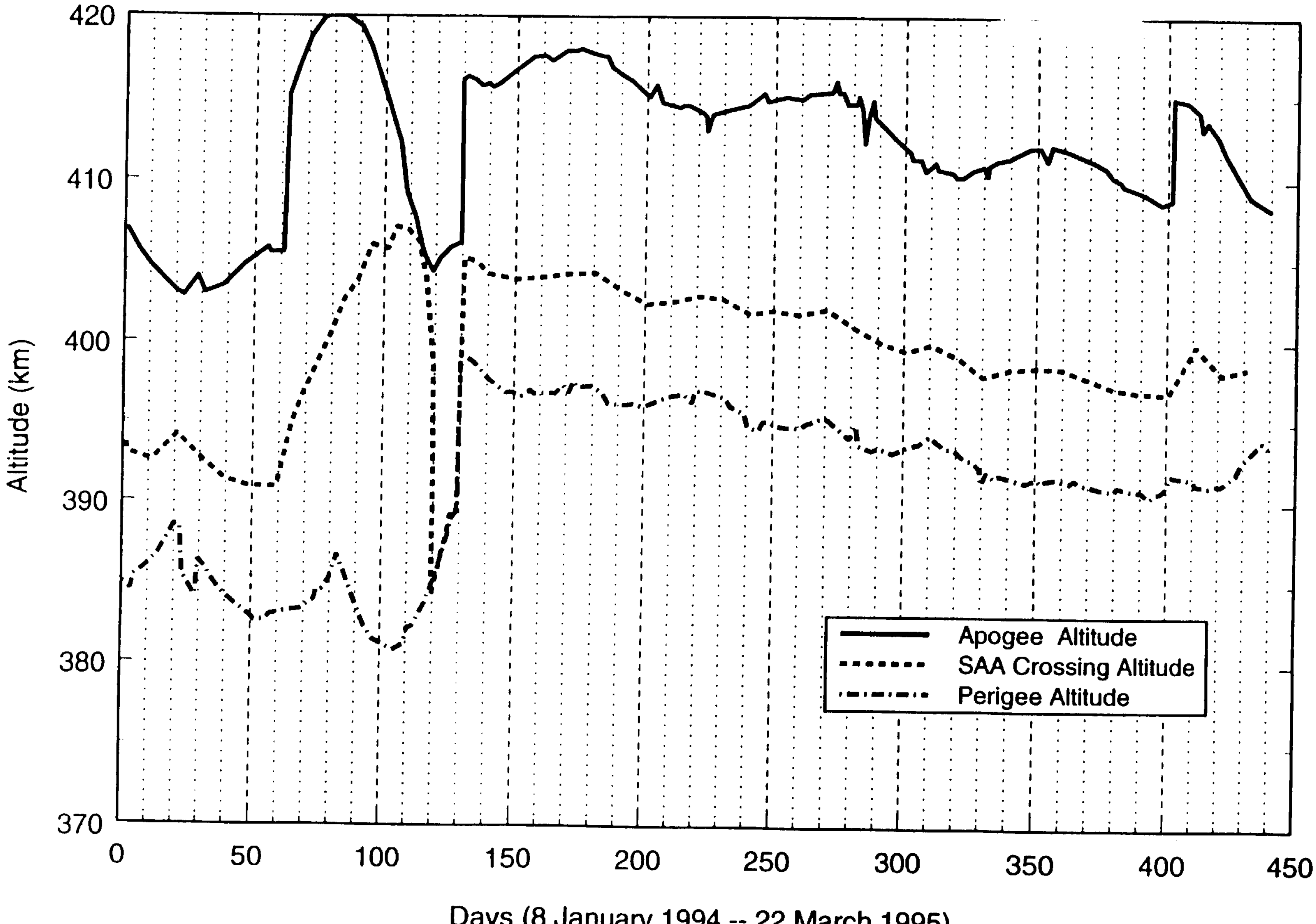

Figure 4-6. Altitude of the Russian Mir Space Station during the ADLET experiments in 1994 – early 1995[28].

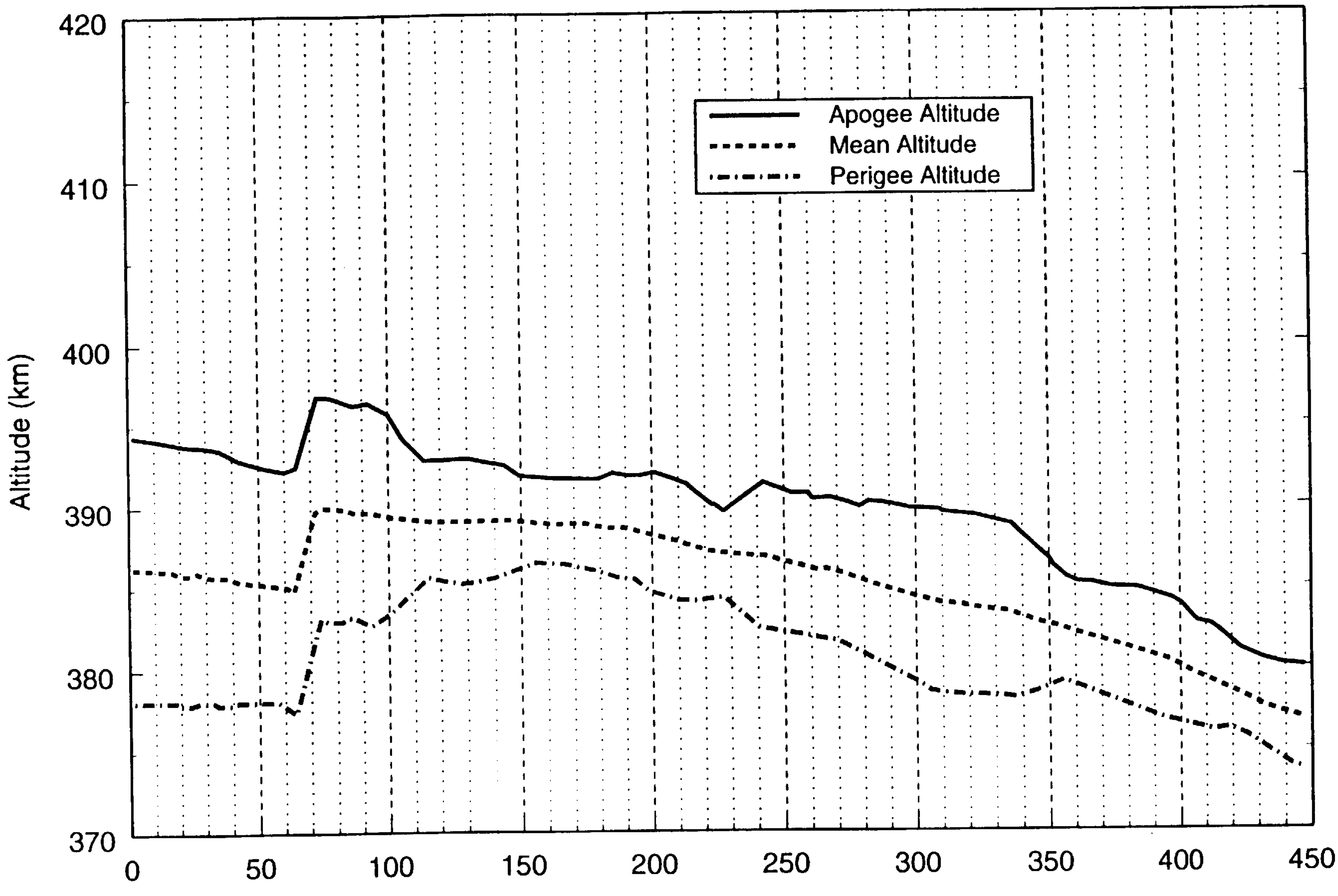

Figure 4-7. Altitude of the Russian Mir Space Station during the NASA/Mir Project from early 1997 to mid-1998[31].

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave Blank)*

2. REPORT DATE
March 1999

3. REPORT TYPE AND DATES COVERED
Contractor Report (Final)

4. TITLE AND SUBTITLE
A Survey of Radiation Measurements Made Aboard Russian Spacecraft in Low-Earth Orbit

5. FUNDING NUMBERS
NAS8–40294

6. AUTHORS
E.R. Benton and E.V. Benton

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
Eril Research, Inc.
P.O. Box 150788
San Rafael, CA 94915–0788

8. PERFORMING ORGANIZATION REPORT NUMBER
M–920

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA/CR—1999–209256

11. SUPPLEMENTARY NOTES
Prepared for the Marshall Space Flight Center for NASA's Space Environments and Effects (SEE) Program
Technical Monitor: J.W. Watts, Jr.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified–Unlimited
Subject Category 93
Standard Distribution

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The accurate prediction of ionizing radiation exposure in low-Earth orbit is necessary in order to minimize risks to astronauts, spacecraft and instrumentation. To this end, models of the radiation environment, the AP–8 trapped proton model and the AE–8 trapped electron model, have been developed for use by spacecraft designers and mission planners. It has been widely acknowledged for some time now by the space radiation community that these models possess some major shortcomings. Both models cover only a limited trapped particle energy region and predictions at low altitudes are extrapolated from higher altitude data. With the launch of the first components of the *International Space Station* with numerous constellations of low-Earth orbit communications satellites now being planned and deployed, the inadequacies of these trapped particle models need to be addressed. Efforts are now underway both in the U.S. and in Europe to refine the AP–8 and AE–8 trapped particle models. This report is an attempt to collect a significant fraction of data for use in validation of trapped radiation models at low altitudes.

14. SUBJECT TERMS
radiation, space radiation, radiation environment

15. NUMBER OF PAGES
104

16. PRICE CODE
A06

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

[25] Petrov, V.M., Tchernykh, I.V., Benghin, V.V., Kolomensky, A.V., Ivanov, Yu. V., Shurshakov, V.A., Filippychev, S.A., and Lyagushin, V.I. "Dose rate measurements in Mir Core Module compartments: Dose-A1 instrument data and model estimations," proceedings of the 3rd Workshop on Radiation Monitoring for the International Space Station, Budapest, Hungary, 24-26 March 1998.

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